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RESEARCH MEMORANDUM

INVESTIGATION OF CONICAL SUBSONIC DIFFUSERS FOR RAM-JET ENGINES

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

INVESTIGATION OF CONICAL SUBSONIC DIFFUSERS FOR RAM-JET ENGINES

By John M. Farley and Henry J. Welna

SUMMARY

As part of an over-all investigation of the performance of a ram-jet combustor, several methods of improving the performance of the combustor-inlet diffuser were investigated. The basic diffuser types investigated were: (1) reversed-bellmouth diffuser, (2) 30° included-angle conical diffuser, (3) 30° conical diffuser with guide vanes, (4) 30° conical diffuser with vortex generators, and (5) 30° conical diffuser with splitter cones.

The investigations were conducted with three different diffuser-inlet velocity profiles, the first two of which were similar and characterized by unsymmetrical circumferential distribution and large boundary layers. The third profile was uniform circumferentially and had much thinner boundary layers. Maximum diffuser efficiencies obtained with the nonuniform and with the uniform inlet profiles were 70 and 72 percent, respectively. These maximum efficiencies were both obtained with vortex-generator configurations and represent efficiency gains of approximately 20 percent over those obtained with the 30° conical diffuser without flow-control devices. In addition, diffuser flow separation was eliminated with these vortex-generator configurations. The guide-vane configurations provided moderate improvement in diffuser efficiency; however, in all cases, combustion occurred in the vane wakes, upstream of the flame holders. The better splitter-cone configurations gave relatively uniform diffuser-outlet profiles but little improvement in diffuser efficiency. One configuration, which incorporated both vortex generators and a splitter cone, gave diffuser efficiencies higher than those obtained with the configuration using the same vortex generators alone and also provided a relatively uniform diffuser-outlet velocity profile.

INTRODUCTION

As part of an over-all program to evaluate and improve the performance of a ram-jet engine, a direct-connect investigation of the

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engine was conducted. The engine included a combustor-inlet diffuser designed to provide transition from the outlet of the supersonic diffuser used in flight (32.2-in. diameter) to the inlet of the 48-inch-diameter engine combustion chamber. The over-all area ratio of the diffuser was 2.22 (without consideration of flame-holder blockage), and because of the relatively short length of the engine, it was necessary that the length of the diffuser be kept to a minimum.

The original contours of the combustor-inlet diffuser were similar to a reversed bellmouth. Initial investigations indicated severe separation in this diffuser section, resulting in combustion upstream of the flame holders, high gas velocities in the region of the flame holders, and low diffuser efficiency. In an effort to improve the diffuser and combustor performance, a large number of diffuser modifications were investigated. Among these modifications were configurations utilizing guide vanes (ref. 1), vortex generators (refs. 2 and 3), and flow-control sleeves or splitter cones. The primary purpose for investigation of the splitter cones was to provide positive fuel stratification, which is desirable in low-temperature-ratio combustors (ref. 4). However, it was believed that splitter cones would alleviate diffuser separation, since air would be channeled along the outer diffuser wall and the divergence angles would be less than that of the original diffuser.

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The investigation was conducted over a range of diffuser-inlet Mach number from about 0.42 to 0.52 with diffuser-inlet total pressures from 1000 to 1220 pounds per square foot absolute. For all diffuser configurations investigated, the combustor flame-holder and fuel-injection systems were installed. Data were obtained both with and without combustion.

The results presented in this report compare performance of the various configurations on the basis of diffuser static-pressure-rise efficiency. Typical diffuser-exit velocity profiles for the various configurations are also compared.

APPARATUS

Installation

A sketch of the ram-jet-engine installation in the altitude chamber is shown in figure 1. The combustion air passes from the inlet-air line into the diffuser section of the test chamber, through smoothing screens, and into the engine-inlet bellmouth. After leaving the engine exhaust nozzle, the gases pass through a water-cooled exhaust extension into the exhaust section. The combustion air was heated to the desired inlet temperature by means of a gas-fired heat exchanger. A periscope was mounted in the exhaust section to permit observation of combustion in the engine.

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In order to improve the diffuser-inlet velocity profiles, two alterations of the inlet ducting were made in the course of the investigation. These alterations were:

(1) A number of angle iron strips were placed across the inlet-diffuser section of the test chamber, as shown in figure 1, in order to provide uniform pressure distribution at the engine-inlet bellmouth.

(2) The throat diameter of the engine-inlet bellmouth was increased from 24 to 27.4 inches to avoid choking.

Description of Original Engine Configuration

A cross section of the original engine configuration is shown in figure 2(a), and an enlargement of the diffuser section showing the original flame holder and diffuser is shown in figure 2(b). The original diffuser had contours similar to a reversed bellmouth. The upstream section of the diffuser was a cone approximately 10 inches long and having an included angle of about 30°. This cone was faired to the 48-inch-diameter combustion chamber with a 50-inch-radius circular arc. The over-all length of the diffuser was 20.6 inches.

Because the flame holders and fuel injectors were in place during the diffuser investigation and occupied a portion of the diffuser, a brief description of these systems is included. The combustor flame-holding system was mounted in the diffuser by means of five radial struts and consisted of primary and secondary flame-holder networks. The primary flame holder consisted of an 8-inch-diameter center pilot burner and five 5-inch-diameter satellite pilot burners attached to the center pilot by radial interconnecting struts. The satellite pilots were also interconnected by means of a segmented annular V-gutter flame holder. The secondary flame holder was an annular V-gutter which was connected to the primary system by means of 10 slanted radial gutters.

A sketch showing a pair of the original fuel-spray bars is presented in figure 3. The original fuel system consisted of 10 pairs of these bars spaced circumferentially around the diffuser at a point approximately 9 inches downstream of the reversed-bellmouth diffuser inlet.

Diffuser Modifications

In addition to the original reversed-bellmouth diffuser, several variations of four basic types of diffuser were investigated. The basic types were: (1) a 30° included-angle conical diffuser, (2) the 30° conical diffuser with guide vanes, (3) the 30° conical diffuser with vortex generators, and (4) the 30° conical diffuser with splitter cones.

A summary of the diffuser configurations investigated is presented in table I. Besides the diffuser changes, several minor flame-holder and fuel-injector changes were made during the diffuser investigation. The flame-holder changes are shown in figure 4, and a column listing the fuel-injection system used for each configuration is included in table I. The afterburner-type fuel injectors, which consisted of twenty 3/8-inch-diameter fuel-spray tubes (configurations SC-5 through SC-7), may be seen in figure 5.

30° Conical diffuser (configurations 2 and 2a). - For the second configuration investigated, the aft portion of the original reversed bellmouth was faired to form a conical diffuser 30.6 inches long and having an included angle of approximately 30° (fig. 4(a)). This conical diffuser was used throughout the remaining portion of the investigation. Configuration 2a had the same diffuser used in configuration 2; however, the flame holder was altered as shown in figure 4.

30° Conical diffuser with guide vanes (configurations GV-1 through GV-3). - Details of the guide-vane configurations are given in figures 6(a) and (b), and a photograph of a typical guide-vane installation is given in figure 6(c). In general, the recommendations of Patterson (ref. 1) were followed in design of the guide-vane configuration. The vanes of configuration GV-1 were truncated cones without camber. Configuration GV-2 was the same as GV-1 except that the first vane was omitted. The vanes of configuration GV-3 had 1/2-inch camber.

30° Conical diffuser with vortex generators (configurations VG-1 through VG-3). - Details of the vortex-generator configurations reported are listed in table II. Configurations VG-1 and VG-2 had vortex generators located 40 and 20 inches, respectively, upstream of the diffuser inlet. Configuration VG-3 had the vortex generators of configuration VG-2 and an additional set located 10 inches downstream of the diffuser inlet. The vortex generators were symmetrical airfoils, and alternate vanes were set at angles of attack of ±13°. A photograph of a typical vortex-generator installation is presented in figure 7.

30° Conical diffuser with splitter cones (configurations SC-1 through SC-8). - The splitter-cone configurations are illustrated and tabulated in figure 8(a), and a typical installation is shown in figure 8(b). The splitter-cone configurations are divided into three groups, the basic cone (between stations 0 and 30.6) being the same for all splitter cones within a given group. Each basic cone was designed to capture a different percentage of the air flow. Configuration SC-1 also had the vortex generators of configuration VG-2 installed on the outer diffuser wall.

Instrumentation

Details of the instrumentation used to determine diffuser performance are given in figures 2 and 4. Diffuser-inlet conditions were determined from measurements of total and static pressure and total temperature made at station 2, which was located 28.35 inches upstream of the diffuser inlet. To determine diffuser-outlet conditions, one total-pressure rake and one static-pressure rake were located at station 4, located 24.25 inches downstream of the diffuser inlet. In addition, six wall static-pressure taps and six boundary-layer total-pressure tubes were spaced longitudinally along the diffuser walls of the reversed-bellmouth and the 30° conical diffusers, as shown in figures 2(b) and 4(a), respectively. All pressures were measured with manometers and were photographically recorded.

PROCEDURE

Setting of Flow Conditions

For all data presented, an engine air flow of approximately 60 pounds per second was set by choking a throttling valve in the inlet-air line and maintaining an inlet-air temperature of approximately 525° F. Diffuser-performance data were obtained both with and without combustion in the engine. With combustion, the diffuser Mach number was varied by changing the engine fuel-air ratio, while the exhaust pressure was maintained low enough to insure choking in the engine exhaust nozzle. Without combustion, variations in diffuser Mach number were obtained by changing the exhaust pressure (engine exhaust nozzle not choked).

Methods of Calculation and Data Qualification

Air flow. - Diffuser air flows and inlet Mach numbers were calculated from the total and static pressures and temperature measured at instrumentation station 2.

Boundary-layer velocities. - Longitudinal boundary-layer velocities were calculated from the static and total pressure measured with the wall static taps and the corresponding total-pressure tubes, which were spaced longitudinally along the diffuser wall (figs. 2 and 4). A constant total temperature, equivalent to the temperature measured at station 2, was assumed in these calculations.

Diffuser-outlet velocity profiles. - Diffuser-outlet velocity profiles were calculated from the total and static pressure measured at instrumentation station 4 and the total temperature measured at station 2. Values of air flow at station 4 were also calculated by using these velocities and the measured static pressure. These air flows varied from about 30 percent more to 20 percent less than the air flows measured at station 2. This variation was attributed to nonsymmetrical circumferential air-flow distribution, to interference of struts and instrumentation located upstream of station 4, and to the inherent difficulty of measuring air flow at low velocities. (An error in pressure measurement of less than 2 percent would account for the maximum air-flow discrepancy.) Although the absolute values of velocity profiles at station 4 are doubtful, it is felt that the relative shapes of the profiles are of significance.

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Splitter-cone air-flow distribution. - The distribution of air flow inside and outside of the splitter cones was determined from integration of the velocity profiles at station 4 and the measured static pressures. The discrepancy in air flows between station 2 and station 4, discussed in the preceding section, causes some doubt as to the accuracy of these distribution values; however, for most of the splitter-cone configurations, the calculated values of air-flow distribution remained essentially constant despite variations in the discrepency between the air flows measured at station 2 and station 4.

Diffuser efficiency. - Because of the limited instrumentation at station 4, the values of total pressure measured at that station were not considered sufficiently accurate to give a true indication of the relative effectiveness of the various diffuser configurations. Therefore, diffuser efficiencies based on the diffuser-outlet static pressure were calculated. This efficiency is defined as the ratio of actual static-pressure rise to theoretical isentropic static-pressure rise between station 2 and the diffuser-outlet station.

$$\eta_d = \frac{p_4 - p_2}{p_{4,id} - p_2} = \frac{(p_4/p_2) - 1}{(p_{4,id}/p_2) - 1} \qquad (1)$$

where

$$\frac{p_{4,id}}{p_2} = \frac{A_2 M_2 \left(1 + \frac{\gamma-1}{2} M_2^2\right)^{1/2}}{A_4 M_{4,id} \left(1 + \frac{\gamma-1}{2} M_{4,id}^2\right)^{1/2}} \qquad (2)$$

$M_{4,id}$ was determined from the isentropic relation

$$\frac{M_{4,id}}{\left(1 + \frac{\gamma-1}{2} M_{4,id}^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}} = \frac{A_2}{A_4} \times \frac{M_2}{\left(1 + \frac{\gamma-1}{2} M_2^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}} \qquad (3)$$

where

η_d diffuser efficiency

p	static pressure
M	Mach number
A	area
γ	ratio of specific heats

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and subscript 2 refers to the diffuser-inlet instrumentation station, subscript 4 refers to the diffuser-outlet stations defined in the following paragraph, and the subscript id refers to the ideal condition.

For the configuration without splitter cones, the outlet static pressure was taken at the diffuser-wall static tap nearest the diffuser-outlet station. This tap was located 4 inches upstream of the diffuser outlet in the reversed-bellmouth diffuser and 3.4 inches upstream of the diffuser outlet in the 30° conical diffuser. Diffuser-area ratios (flame-holder blockage accounted for) between station 2 and the planes of these static taps were 2.0 for the reversed-bellmouth diffuser and 2.21 for the conical diffuser.

For the splitter-cone configurations, the diffuser-outlet static pressure was taken as the average stream static pressure measured at station 4, which was located 6.35 inches upstream of the diffuser outlet. The diffuser-area ratio (with flame-holder blockage accounted for) between station 2 and station 4 was 2.11.

In order to relate diffuser performance to engine thrust, it is desirable that the performance in terms of diffuser total-pressure ratio be known. The static-pressure-rise efficiencies presented herein may be converted directly to total-pressure ratios by using the curves of figure 9, in which total-pressure ratio is shown as a function of diffuser efficiency for various inlet Mach numbers and area ratios.

RESULTS AND DISCUSSION

Variations in Diffuser-Inlet Profiles

The first few test runs showed that at the engine diffuser inlet (station 2) the total-pressure profiles had large circumferential and radial variations and that these variations increased with increasing diffuser-inlet Mach number (fig. 10(a)). These variations were attributed both to distortions in the inlet air that were not removed by the smoothing screens and to the existence of supersonic flow and resulting shock waves in the engine-inlet ducting, caused by choking of the 24-inch-diameter throat of the inlet bellmouth. In the course of the investigation, these distortions were alleviated in two steps:

(1) Blockage was added in the tank-inlet transition section (see APPARATUS). This change improved the inlet profiles slightly, but the profiles were still considered unsatisfactory (fig. 10(b)).

(2) The throat diameter of the inlet bellmouth was increased from 24 inches to 27.4 inches to avoid supersonic velocities. This change eliminated the circumferential variations and greatly reduced the boundary-layer thickness (fig. 10(c)). The original inlet configuration and the first and second modifications shall hereinafter be referred to as inlet conditions A, B, and C, respectively.

Although it was desired to obtain the final performance with relatively uniform inlet profiles (inlet condition C), the performance with the nonsymmetrical profiles is of interest because it represents that which might be obtained in a nonsymmetrical supersonic diffuser (e.g., with side or scoop inlets). Therefore, data obtained with the less favorable inlet profiles are included in this report. The inlet condition for each configuration is listed in table I.

In this investigation, development of the combustor-inlet diffuser and the combustor was carried on simultaneously. Consequently, when some of the diffuser modifications were made, the flame-holder or the fuel-spray system, or both, were also modified. Although it was not possible to isolate the relative effects of these simultaneous combustor and diffuser changes, the effects of these combustor modifications on diffuser performance are considered to be of secondary importance.

Performance of Configurations Investigated with Inlet Condition A

Performance of the two configurations investigated with inlet condition A, the original reversed bellmouth (configuration 1) and the 30° conical diffuser (configuration 2), is shown in figure 11. Diffuser efficiencies obtained with the original reversed-bellmouth diffuser were between 0.47 and 0.50 over the range of diffuser-inlet Mach number investigated (fig. 11(a)). Data points obtained with cold flow and with the combustor operating are included in this plot. Agreement between the cold-flow and burning data was good for this configuration and all others for which cold-flow data were taken. A typical diffuser-outlet velocity profile is shown in figure 11(b) for a diffuser-inlet Mach number of 0.46, approximately the design value for the engine. This profile shows a region of flow separation along the diffuser wall. The longitudinal profile of boundary-layer velocity, which was obtained with the same diffuser-inlet Mach number, is presented in figure 11(c). This plot shows that the separation occurred between 14 and 15 inches downstream of station 0.

In order to reduce the adverse pressure gradients and turning angle in the aft portion of the diffuser, the circular-arc portion of the reversed bellmouth was faired to form a continuous 30° included-angle conical diffuser. Efficiencies obtained with this diffuser were approximately the same as those obtained with the reversed bellmouth (fig. 11(a)). The diffuser-outlet velocity profiles indicated that no separation occurred (fig. 11(b)); however, from observation of the flame pattern with the combustor operating, it was apparent that separation was occurring at other circumferential positions. This asymmetrical flow is characteristic of diffusers operating with separated regions. It is also noted that the pressure rake at station 4 was located in the circumferential region of highest inlet velocities (see figs. 4(b) and 10(a)). Boundary-layer velocity instrumentation was not installed for this configuration.

In general, the performance of the 30° conical diffuser was no better than that of the reversed-bellmouth diffuser. Apparently separation occurred far enough upstream in both configurations that the change in the shape of the downstream portion of the diffuser had negligible effect. Both configurations were considered unsatisfactory because of their low efficiency and unstable (separated) characteristics.

Performance of Configurations Investigated with Inlet Condition B

The first change to improve the inlet velocity profiles was made at this point in the investigation. Also, because the limited engine length prohibited any further reduction in the diffuser included angle, it became apparent that some method of flow control would be necessary in order to obtain efficient diffusion in the short length available. Although the performance of the 30° conical diffuser was no better than that of the reversed-bellmouth diffuser, it was felt that, because of the lower diffusion rate of the aft portion of the 30° diffuser, it should be easier to eliminate separation with this shape than with the reversed-bellmouth contour. Therefore, this diffuser shape was used with various flow-control devices for the remaining portion of the investigation.

Guide vanes. - Performance of the two guide-vane configurations investigated with inlet condition B is shown in figure 12. In spite of the more uniform inlet profiles, the diffuser efficiencies (fig. 12(a)) obtained with the first guide-vane configuration (GV-1) were slightly lower than those obtained with the reversed bellmouth or the 30° cone. No separated regions were indicated by the velocity profiles (fig. 12(b)); however, when the combustor was operating, flame was observed in the region downstream of the vanes. It appeared that the combustion in the vane wakes was caused by the first vane; therefore, for the next run, this vane was omitted. This change resulted in an increase in diffuser efficiency to an average value of about 0.60

(fig. 14(a), configuration GV-2). However, the diffuser-outlet velocity profiles were about the same as for the previous configuration (fig. 14(b)), and combustion still occurred in the vane wakes. It therefore appeared that, in order to obtain a satisfactory turning-vane design, a lengthy and detailed development program would be required and that a satisfactory diffuser could be developed more rapidly with other methods of flow control.

Vortex generators. - Other investigators have obtained significant improvement in diffuser performance by means of vortex generators which consisted of short airfoils mounted circumferentially around the perimeter of the diffuser-inlet section. For example, Valentine and Carroll (ref. 3) utilized vortex generators to obtain a significant improvement in the efficiency of a 2:1 area ratio, 23° conical diffuser. It was decided, therefore, that various arrangements of vortex generators should be investigated.

The performance of three vortex-generator configurations investigated with inlet condition B is presented in figure 13. With the first configuration (VG-1, vortex generators 40 in. upstream of station 0), a maximum diffuser efficiency of about 0.70 was obtained (fig. 13(a)). This was the highest efficiency obtained among the configurations investigated with inlet condition B and represents a 20-percent gain over the efficiency obtained with the 30° cone without flow-control devices (fig. 11(a)). The diffuser-outlet velocity profiles showed a fairly steep gradient along the diffuser outer wall, but no separation was apparent (fig. 13(b)). The longitudinal profiles of boundary-layer velocity confirmed the absence of flow separation (fig. 13(c)).

For the next run (VG-2), the vortex generators were moved downstream to a point 20 inches ahead of station 0 in order to determine the effect of longitudinal location and also because the vortex generators in the upstream location interfered with the pressure measurements at station 2. This change resulted in an average decrease in diffuser efficiency of about 0.10 (fig. 13(a)). The diffuser-outlet velocity profiles were similar to but slightly flatter than those obtained with configuration VG-1 (fig. 13(b)), and the boundary-layer velocities were slightly higher in the rear portion of the diffuser (fig. 13(c)).

For configuration VG-3, the vortex generators of configuration VG-2 were used, and an additional set of generators was mounted in a plane 10 inches downstream of station 0. The diffuser efficiencies and velocity profiles were about the same as those obtained with the previous configuration. Apparently the second stage was placed too far downstream in the diffuser to have any beneficial effect.

Splitter cone. - Other investigators have succeeded in improving the combustion efficiency of low-temperature-ratio ram-jet combustors by the use of control sleeves, which provide locally rich fuel-air ratios with low over-all fuel-air ratios (ref. 4). A conical sleeve or splitter cone in the present engine would also channel air along the outer diffuser wall and might prevent separation. In view of these possibilities, it was decided that this type of diffuser modification would merit investigation.

The one splitter-cone configuration investigated with inlet condition B (configuration SC-1) had the vortex generators of configuration VG-2 installed. Performance of this configuration is shown in figure 14. The maximum diffuser efficiency was about 0.61 at a diffuser-inlet Mach number of 0.425, and the efficiency decreased with increasing diffuser-inlet Mach number (fig. 14(a)). This maximum efficiency is about 0.03 higher than that obtained with the configuration having vortex generators alone (VG-2). The diffuser-outlet velocity profiles were flat outside the cone except for the normal boundary layer. Inside the cone, the velocity profiles were fairly uniform near the cone wall, but a fairly thick boundary layer existed along the pilot (fig. 14(b)). The variation of percent air flow through the cone with diffuser-inlet Mach number is shown in figure 14(c). As diffuser-inlet Mach number increased from 0.42 to 0.47, the amount of air captured by the cone decreased from 64 to 49 percent. The relatively good performance of this configuration is attributed to: (1) the small diffusion angle inside the cone, and (2) the vortex generators, which promote efficient diffusion of the air flowing around the cone (as indicated by the flat diffuser-outlet velocity profile).

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Performance of Configurations Investigated with Inlet Condition C

At this point in the investigation, the second modification to improve the diffuser-inlet velocity profiles was made (i.e., the throat diameter of the engine-inlet bellmouth was increased from 24 to 27.4 in.).

Splitter cones. - Most of the diffuser modifications investigated with inlet condition C were variations of splitter-cone design. At the time the first of these splitter cones (SC-2) was installed, the fuel-injection bars were moved to a point 18 inches upstream of station 0. To prevent main-stream fuel from entering the center pilot burner, it was necessary to add the pilot extension shown in figure 4. The vortex generators around the outside of the extension were installed for the purpose of promoting fuel-air mixing.

The basic cone of the first two splitter-cone configurations (SC-2 and SC-3) investigated with inlet condition C was the same as that used for configuration SC-1; however, a 23.3-inch-long extension was added to the upstream end of the cone to prevent main-stream fuel from entering the annular passage. Also, the diffuser vortex generators (VG-2) were removed. Configuration SC-3 was the same as SC-2 except that vortex generators were added to the inside of the cone at station 0 to promote fuel-air mixing. Performance of configurations SC-2 and SC-3 is shown in figure 15.

The maximum efficiency obtained with configuration SC-2 was about 0.54 (fig. 15(a)), a decrease of about 0.07 from the maximum efficiency of configuration SC-1. This reduction in efficiency is attributed to separation which occurred along the diffuser wall (fig. 15(b)) and further illustrates the effectiveness of the vortex generators used with configuration SC-1 (especially when it is considered that the inlet velocity profiles were more uniform for configuration SC-2). Except for a slight reduction in diffuser efficiency at lower inlet Mach numbers, the performance of configuration SC-3 was about the same as that of configuration SC-2.

The basic splitter cone (group II) of configurations SC-4 and SC-5 was designed to capture a greater portion of the air than the previous cones in order to shift the engine combustion-efficiency peak to a higher value of fuel-air ratio. Performance of these configurations is shown in figure 16. The maximum diffuser efficiency obtained with configuration SC-4 was about 0.58 (fig. 16(a)). The velocity profiles indicated separation along the outer diffuser wall (fig. 16(b)). About 77 percent of the air passed through the cone for all values of diffuser-inlet Mach number (fig. 16(c)).

For configuration SC-5, the upstream end of the cone was altered to reduce the capture area. This change resulted in a large decrease in diffuser efficiency (fig. 16(a)). The velocity profiles showed that the separation in the outer passage that had occurred with configuration SC-4 was eliminated and that a very large separated region existed along the center pilot (fig. 16(b)). The large decrease in efficiency is attributed to this separation. Apparently the reduction in cone inlet area allowed enough high-energy air to enter the outer passage to eliminate separation in that region, but also increased the expansion ratio in the inner passage so greatly that separation occurred along the pilot wall. Flow conditions along the center pilot were also aggravated by air spilling around the pilot inlet, which was greatly oversized for the pilot air flows obtained. About 58 percent of the air passed through this cone (fig. 16(c)).

The basic cone (group III) of configurations SC-6 through SC-8 was intermediate in size between the basic cones of the previous configurations. Performance of these configurations is shown in figure 17. The maximum diffuser efficiency obtained with configuration SC-6 was about 0.55 (fig. 17(a)). The velocity profiles were relatively uniform (fig. 17(b)), and between 58 and 60 percent of the air passed through the cone for all values of diffuser-inlet Mach number (fig. 17(c)).

Configuration SC-7 was the same as SC-6 except that 24 vortex generators were added inside the cone at station 0 to promote fuel-air mixing. At high values of diffuser-inlet Mach number, the diffuser efficiencies obtained with this configuration (fig. 17(a)) were slightly higher than those obtained with the previous configuration. The velocity profiles were about the same except that the velocity peak along the inside of the cone was eliminated (fig. 17(b)), and air flow through the cone was reduced to about 56 percent (fig. 17(c)). From the changes in velocity profile and cone air flow, it appears that the vortex generators effectively increased the blockage within the cone.

For configuration SC-8, a 10-inch-long cylindrical extension was added to the downstream end of the previous splitter-cone configuration in order to maintain fuel stratification to a point closer to the secondary flame holder. The maximum diffuser efficiency was about 0.58, slightly higher than that of the previous configuration (fig. 17(a)), and the velocity profiles and percentage air flow through the cone were about the same.

Comparison of diffuser types. - One guide-vane configuration (GV-3), one vortex-generator configuration (VG-2), and the 30° conical configuration (configuration 2a) also were investigated with inlet condition C. The performance of these configurations and that of splitter-cone configuration SC-8 are compared in figure 18.

A maximum diffuser efficiency of 0.72 was obtained with the vortex-generator configuration (VG-2) - the highest efficiency obtained in the course of the investigation. This efficiency is about 0.19 higher than that obtained with the 30° conical configuration (2a) with the same inlet condition (fig. 18(a)). With a diffuser-inlet Mach number of 0.42, this efficiency gain corresponds to an increase in diffuser total-pressure recovery from 0.96 to 0.975. This efficiency is also 0.14 higher than obtained with the same configuration with inlet condition B (fig. 13(a)).

It is recalled that with inlet condition B, higher efficiency was obtained with configuration VG-1 (vortex generators 40 in. upstream of station 0) than with VG-2 (vortex generators 20 in. upstream of station 0). It is therefore probable that efficiencies higher than 0.72 could be obtained with inlet condition C if the vortex generators were moved further upstream. Reference 3 reports that a maximum diffuser-exit efficiency of about 0.83 was obtained in an investigation of a 2:1 area ratio, 23° conical diffuser by using various vortex-generator configurations. This efficiency was based on incompressible-flow relations, and when corrected for compressibility, the value was reduced to about 0.79. Also, the diffuser was not obstructed by flame holders, fuel spray bars, etc. With consideration of the higher diffusion angle and the obstructions in the present diffuser, the maximum efficiency value of 0.72 appears to compare favorably with that of reference 3. In addition to being the most efficient, the vortex-generator configuration gave the most uniform diffuser-outlet velocity profile.

The guide-vane configuration was next highest in efficiency with a maximum of 0.66, about 0.13 higher than that obtained with the 30° cone alone. Diffuser-outlet velocity profiles showed a fairly thick boundary layer at the outer diffuser wall and separation along the center pilot. This separation was probably aggravated by air spilling around the oversized pilot air inlet (see Splitter cones). Also, when the combustor was operating, combustion occurred in the vane wakes as it did with the other guide-vane configurations investigated, which leads to the conclusion that the guide-vane design is quite critical, especially when fuel is sprayed upstream of the vanes.

The splitter-cone configuration gave efficiencies which averaged only about 0.04 higher than the conical diffuser without flow-control devices. The diffuser-outlet velocity profiles, however, were fairly uniform except for boundary layers in the outer annulus. In general, the performance of the various splitter-cone configurations indicates that, with such a short diffuser, it is not possible to greatly increase the diffuser efficiency with a single cone without additional flow control. However, by use of a good vortex-generator design in conjunction with a properly designed splitter cone, considerable improvement in diffuser performance may be obtained over that of the conical diffuser.

The efficiency of the 30° conical diffuser (fig. 18(a)) was only about 0.04 higher than the efficiency of the same diffuser with inlet condition A (fig. 11(a)). The diffuser-outlet velocity profiles (fig. 18(b)) indicated that, even with the improved inlet velocity profile, separation occurred along the outer diffuser wall. The slight improvement in efficiency was probably due to movement of the separation point slightly further downstream with the improved inlet velocity profiles.

CONCLUDING REMARKS

The best diffuser performance was obtained with a configuration having vortex generators 20 inches upstream of the diffuser inlet and a uniform inlet velocity profile. The maximum diffuser efficiency was 0.72 as compared with 0.53 obtained with the 30° conical diffuser with the same inlet profile. With a diffuser-inlet Mach number of 0.42, this would correspond to an increase in diffuser total-pressure ratio from 0.96 to 0.975. The maximum efficiency compares favorably with results obtained by other investigators with a 2:1 area ratio, 23° unobstructed conical diffuser incorporating vortex generators. In addition to the increase in diffuser efficiency obtained by use of the vortex generators, the diffuser-outlet profiles were more uniform and separation was eliminated.

Improving the uniformity of the diffuser-inlet velocity profile (inlet condition A or B to C) resulted in an increase of 0.04 in the efficiency of the 30° conical diffuser and of 0.14 in the efficiency of the configuration with vortex generators 20 inches upstream of the diffuser inlet. The highest diffuser efficiency (0.70) with inlet condition B was obtained with vortex generators 40 inches upstream of the diffuser inlet. This efficiency was about 0.10 higher than the efficiency obtained with vortex generators 20 inches upstream of the diffuser inlet and with the same inlet profile.

The better splitter-cone configurations investigated gave efficiencies only slightly higher than the 30° conical diffuser with the same inlet profile. However, a splitter-cone configuration which also had vortex generators on the outer diffuser wall gave efficiencies as high as 0.61 with inlet condition B. This was an increase of 0.03 over the configuration with vortex generators alone (VG-2) with similar inlet profiles. Fairly uniform diffuser-outlet profiles without separation were obtained with the better splitter-cone configurations.

The best guide-vane configurations gave efficiencies about 0.13 higher than the 30° conical diffuser (inlet condition C). The guide-vane configurations were, however, considered unsatisfactory because in all cases combustion occurred upstream of the flame holder in the vane wakes.

Performance of the 30° conical diffuser was almost identical with that of the original reversed bellmouth. With both configurations, separation occurred far enough upstream that the contour change in the downstream portion of the diffuser had no significant effect.

The efficiency of a 30° conical diffuser was therefore improved as much as 20 percent and separation was eliminated by the use of vortex generators. The use of splitter cones gave only small efficiency gains, but relatively uniform diffuser-outlet velocity profiles were obtained with the better designs. A configuration which incorporated both vortex generators and a splitter cone gave efficiencies higher than those obtained with any other splitter-cone configuration and also higher than those obtained when the same vortex generators were used without the splitter cone. Moderate diffuser-efficiency increases were obtained with guide vanes; however, in all cases, combustion occurred in the vane wakes.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 22, 1953

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1. Patterson, G. N.: Modern Diffuser Design. Aircraft Eng., vol. X, no. 115, Sept. 1938, pp. 267-273.

2. Taylor, H. D.: Application of Vortex Generator Mixing Principle to Diffusers. Rep. No. R-15064-5, Res. Dept., United Aircraft Corp., East Hartford (Conn.), Dec. 31, 1948. (Air Force Contract W33-038 ac-21825.)

3. Valentine, E. Floyd, and Carroll, Raymond B.: Effects of Several Arrangements of Rectangular Vortex Generators on the Static-Pressure Rise Through a Short 2:1 Diffuser. NACA RM L50L04, 1951.

4. Trout, Arthur M., and Wentworth, Carl B.: Free-Jet Altitude Investigation of a 20-Inch Ram-Jet Combustor with a Rich Inner Zone of Combustion for Improved Low-Temperature-Ratio Operation. NACA RM E52L26, 1953.

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TABLE I. - SUMMARY OF DIFFUSER CONFIGURATIONS

Configuration	Description	Reference for details	Inlet condition (fig. 10)	Fuel-spray system (fuel-spray-bar location referred to station 0)
1	Reversed bellmouth	Fig. 2	A	Original, 9 in. downstream
2	30° cone	Fig. 4	A	Original, 9 in. downstream
2a	30° cone, modified flame holder	Fig. 4	C	Original, 18 in. upstream
GV-1	Guide vanes	Fig. 6	B	Original, 9 in. downstream
GV-2	Guide vanes	Fig. 6	B	Original, 9 in. downstream
GV-3	Guide vanes	Fig. 6	C	Original, 9 in. downstream
VG-1	Vortex generators	Table II	B	Original, 9 in. downstream
VG-2	Vortex generators	Table II	B and C	Original, 9 in. downstream
VG-3	Vortex generators	Table II	B	Original, 9 in. downstream
SC-1	Splitter cone with VG-2	Fig. 8	B	Original, 9 in. downstream
SC-2	Splitter cone	Fig. 8	C	Original, 18 in. upstream
SC-3	Splitter cone	Fig. 8	C	Original, 18 in. upstream
SC-4	Splitter cone	Fig. 8	C	Original, 18 in. upstream
SC-5	Splitter cone	Fig. 8	C	Afterburner, 11 in. downstream
SC-6	Splitter cone	Fig. 8	C	Afterburner, 11 in. downstream
SC-7	Splitter cone	Fig. 8	C	Afterburner, 11 in. downstream
SC-8	Splitter cone	Fig. 8	C	Original, 18 in. upstream

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TABLE II. - DESCRIPTION OF VORTEX-GENERATOR CONFIGURATIONS

Configuration	Longitudinal location, engine station	Angle of attack	Chord, in.	Span, in.	Maximum thickness, in.	Number used
VG-1	-40.0	±13°	5.0	2.5	0.625	16
VG-2	-20.0	±13°	5.0	2.5	.625	16
VG-3	-20.0	±13°	5.0	2.5	.625	16
	10.0	±13°	5.0	2.5	.625	20

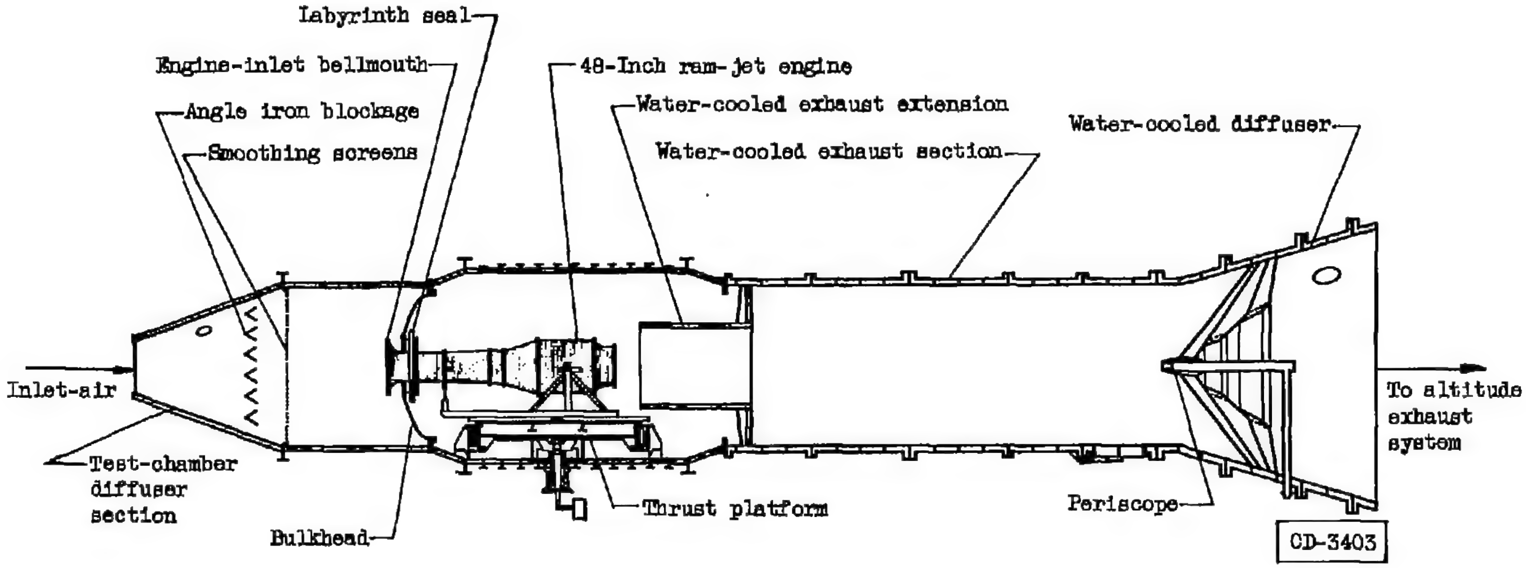
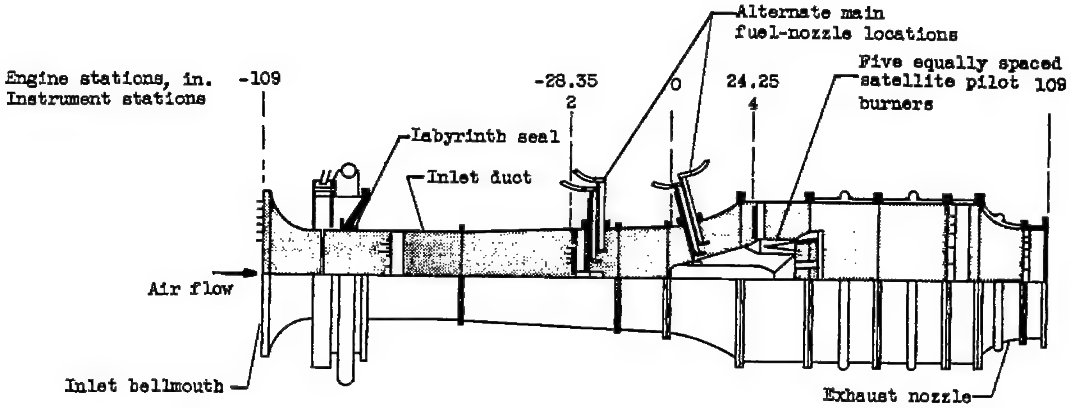
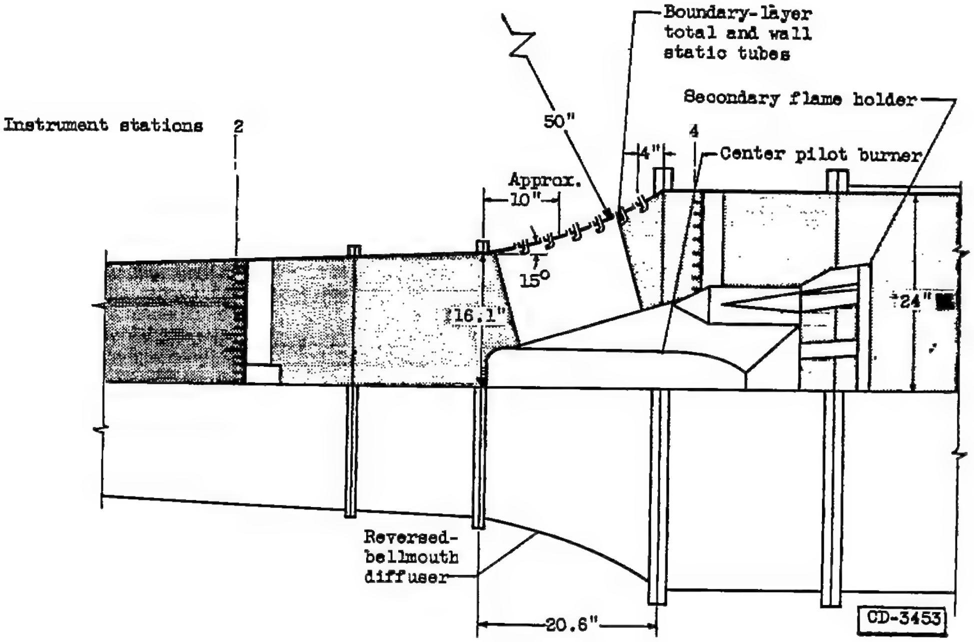

Labyrinth seal
Engine-inlet bellmouth
Angle iron blockage
Smoothing screens
48-Inch ram-jet engine
Water-cooled exhaust extension
Water-cooled exhaust section
Water-cooled diffuser
Inlet-air
To altitude exhaust system
Test-chamber diffuser section
Bulkhead
Thrust platform
Periscope
CD-3403

Figure 1. - 48-Inch ram-jet engine in 14-foot-diameter altitude chamber.


Alternate main fuel-nozzle locations
Engine stations, in.
Instrument stations
-109
-28.35
2
0
24.25
4
Five equally spaced satellite pilot burners
109
Labyrinth seal
Inlet duct
Air flow
Inlet bellmouth
Exhaust nozzle

(a) Engine with inlet ducting.


Boundary-layer total and wall static tubes
Secondary flame holder
Instrument stations
2
50"
4
4"
Center pilot burner
Approx.
10"
15°
16.1"
24"
Reversed-bellmouth diffuser
20.6"
CD-3453

(b) Diffuser section showing flame holder and instrumentation.

Figure 2. - Original engine (configuration 1).

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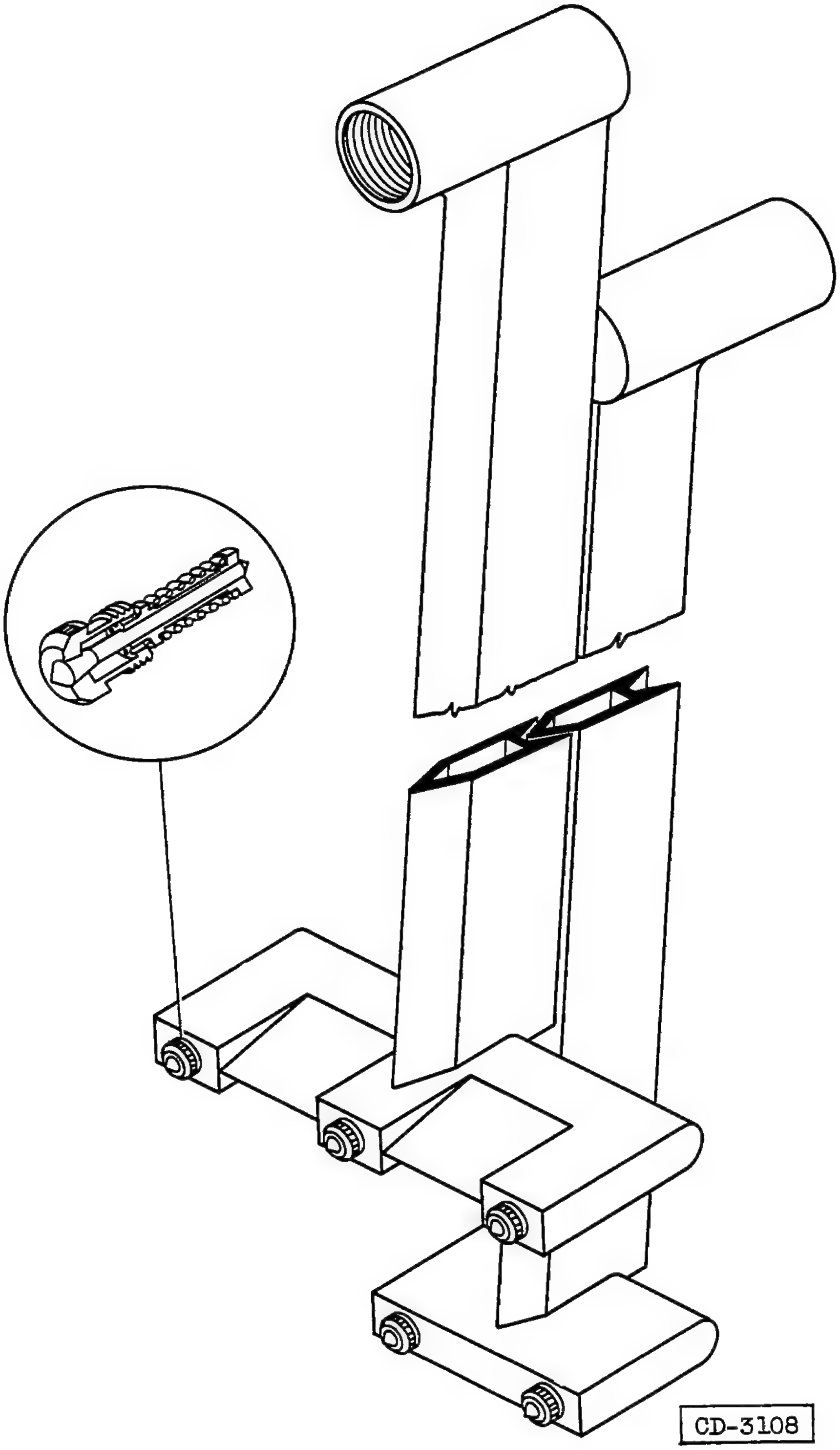
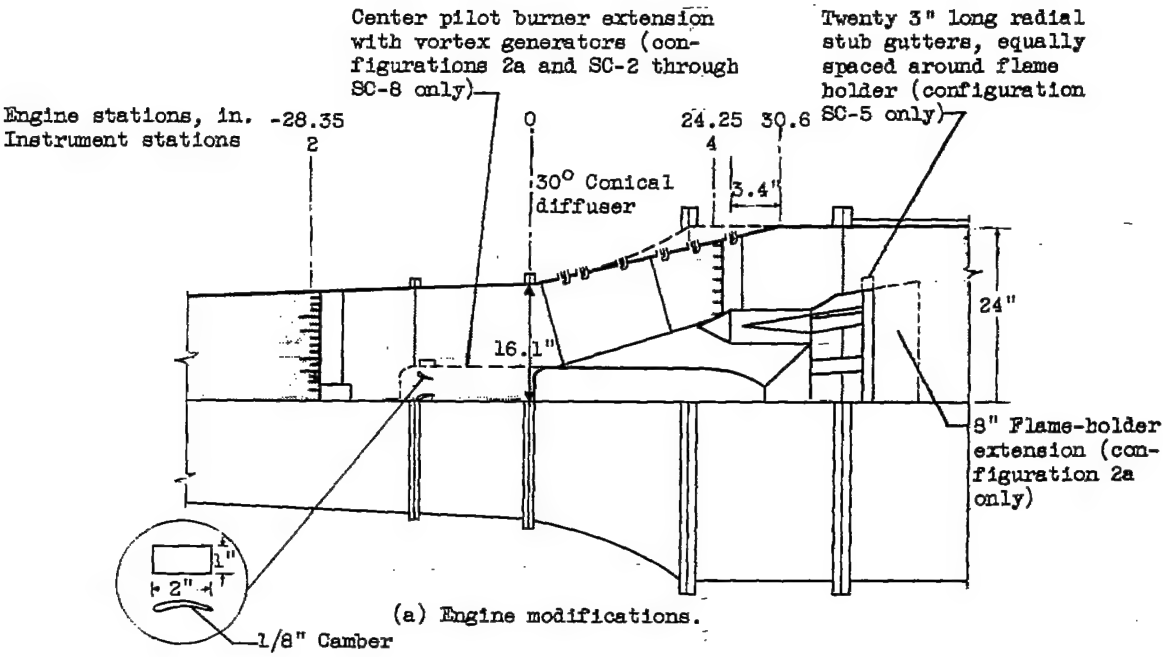
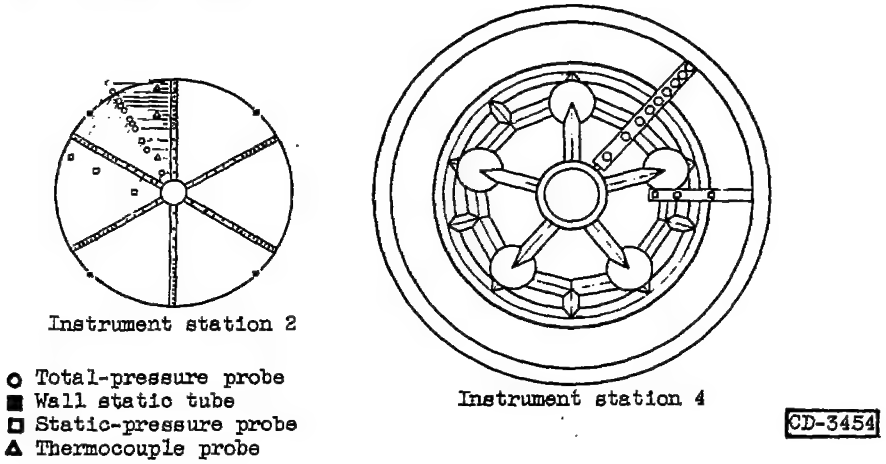


Figure 3. - Original fuel-spray bars.


Center pilot burner extension with vortex generators (configurations 2a and SC-2 through SC-8 only)
Twenty 3" long radial stub gutters, equally spaced around flame holder (configuration SC-5 only)
Engine stations, in.
Instrument stations
-28.35
2
0
24.25
4
30.6
30° Conical diffuser
3.4"
24"
16.1"
8" Flame-holder extension (configuration 2a only)
1"
2"
1/8" Camber

(a) Engine modifications.


Instrument station 2
Instrument station 4
○ Total-pressure probe
■ Wall static tube
□ Static-pressure probe
▲ Thermocouple probe
CD-3454

(b) Cross sections showing instrumentation details (viewed looking downstream).

Figure 4. - Engine modifications and diffuser instrumentation.

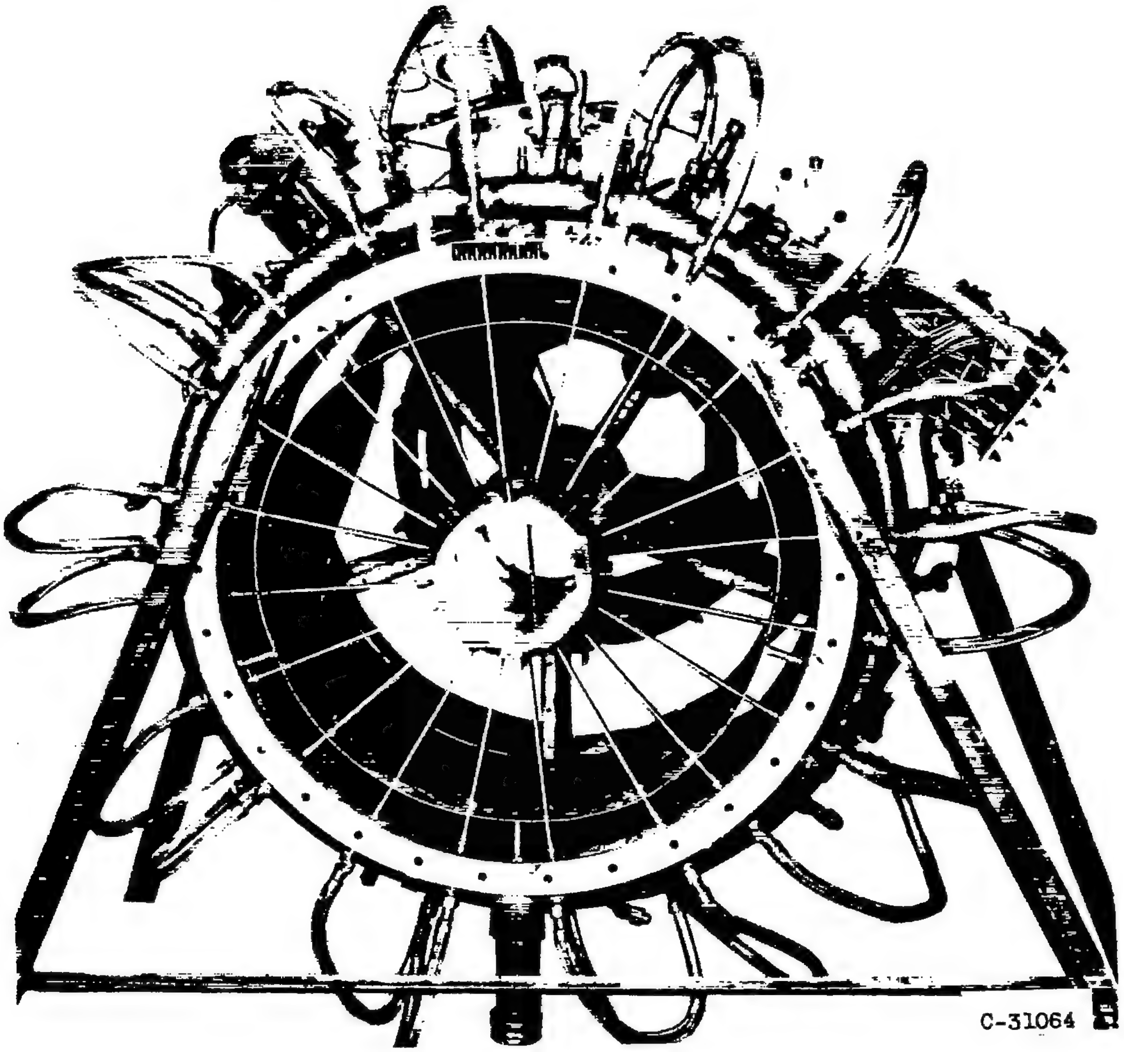
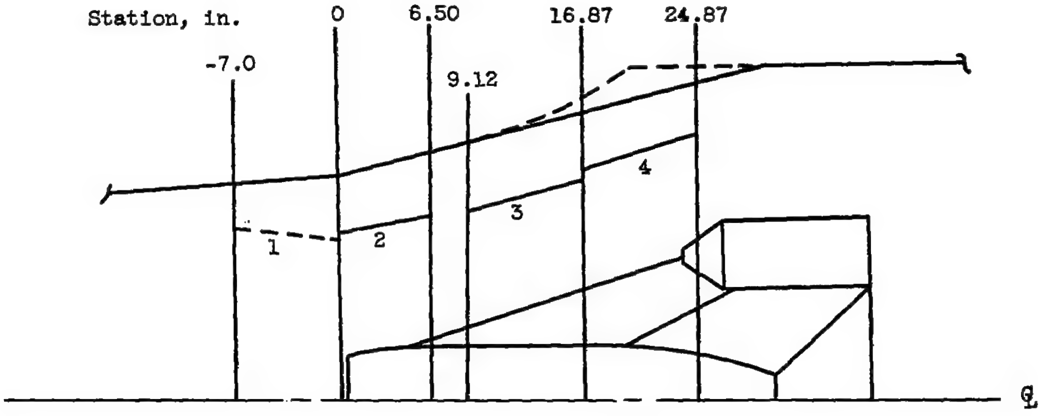
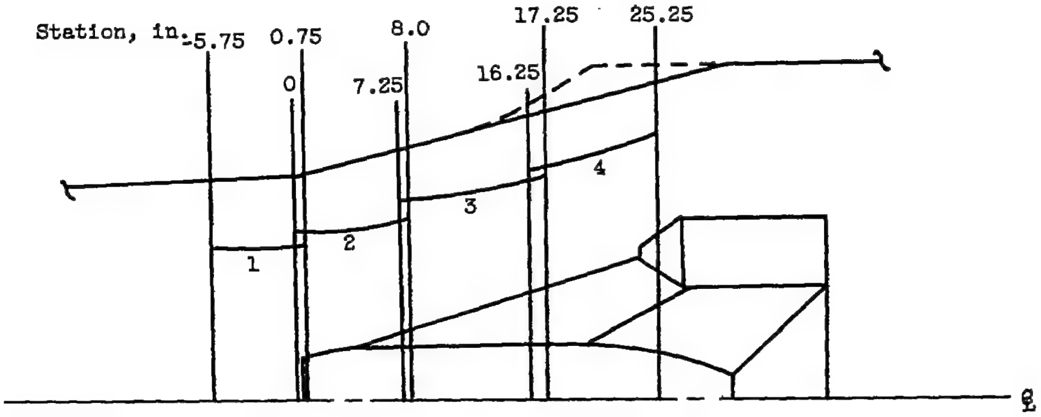


Figure 5. - Upstream view of diffuser showing installation of afterburner-type fuel-spray bars.


Station, in.
-7.0
0
6.50
9.12
16.87
24.87
1
2
3
4
℄

Vane	Station					
	-7.0	0	6.50	9.12	16.87	24.87
	Distance from center line, in.					
1	12.25	11.75	-----	-----	-----	-----
2	-----	12.25	13.25	-----	-----	-----
3	-----	-----	-----	13.82	16.0	-----
4	-----	-----	-----	-----	16.62	19.0

(a) Configurations GV-1 and GV-2. (Vanes 1, 2, 3, and 4 used for GV-1; and vanes 2, 3, and 4 used for GV-2.)


Station, in.
-5.75
0.75
0
8.0
7.25
17.25
16.25
25.25
1
2
3
4
℄

Vane	Station							
	-5.75	0	0.75	7.25	8.00	16.25	17.25	25.25
	Distance from center line, in.							
1	11.0	-----	11.25	-----	-----	-----	-----	-----
2	-----	12.25	-----	-----	13.25	-----	-----	-----
3	-----	-----	-----	14.12	-----	-----	16.06	-----
4	-----	-----	-----	-----	-----	16.87	-----	19.12

(b) Configuration GV-3.

Figure 6. - Guide-vane configurations.

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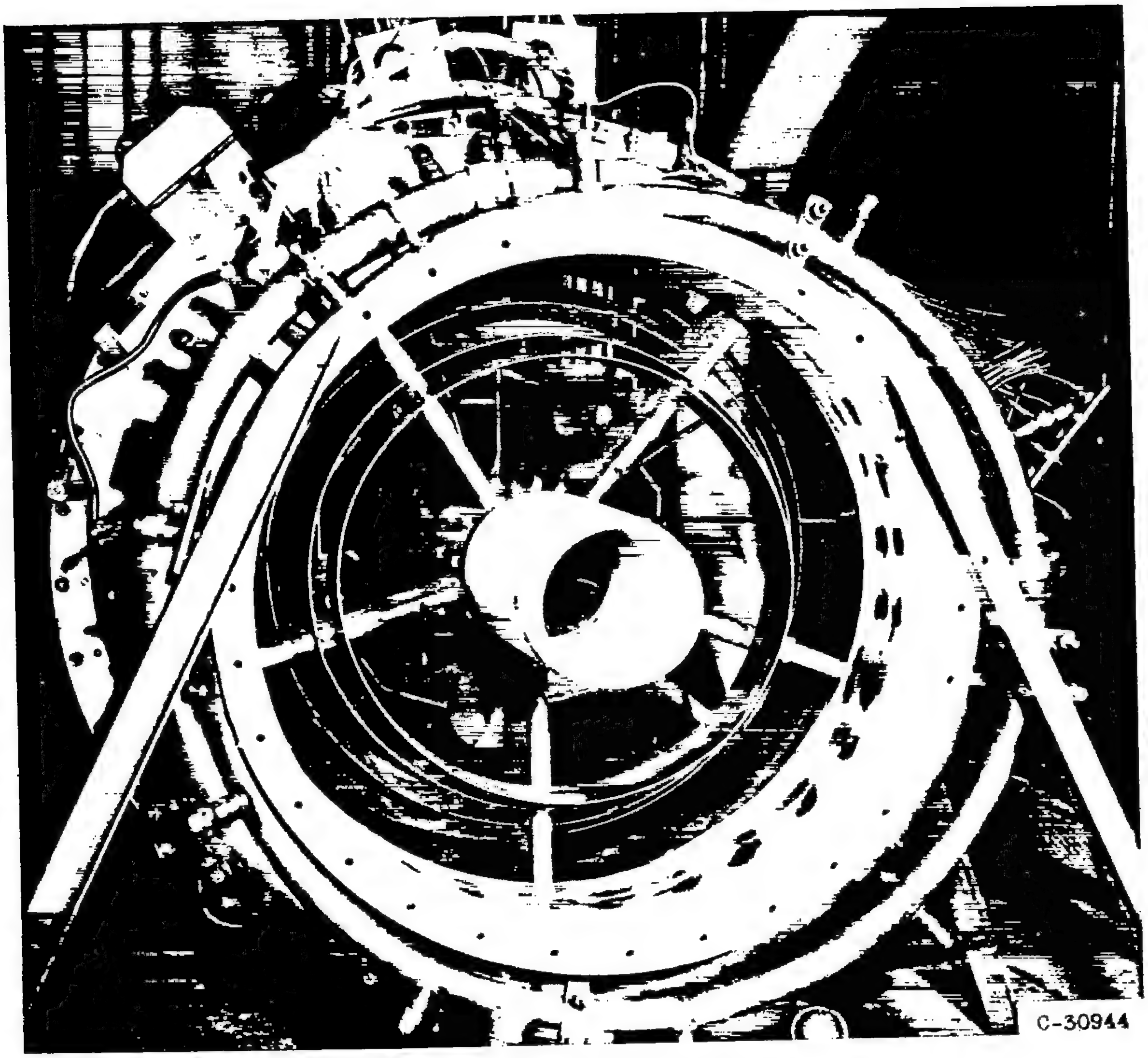
CV-4



(c) Typical installation (upstream view).

Figure 6. - Concluded. Guide-vane configurations.

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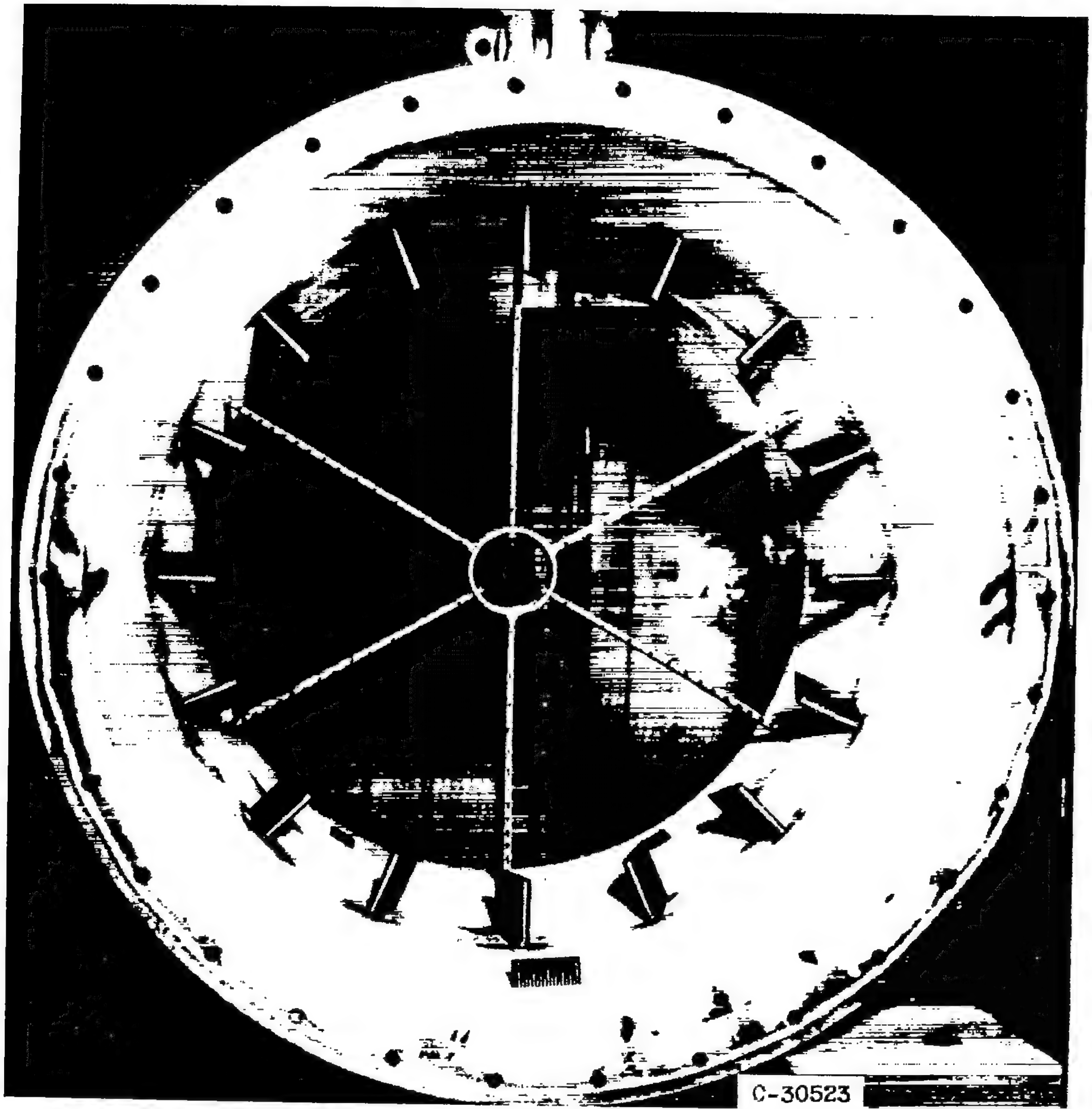
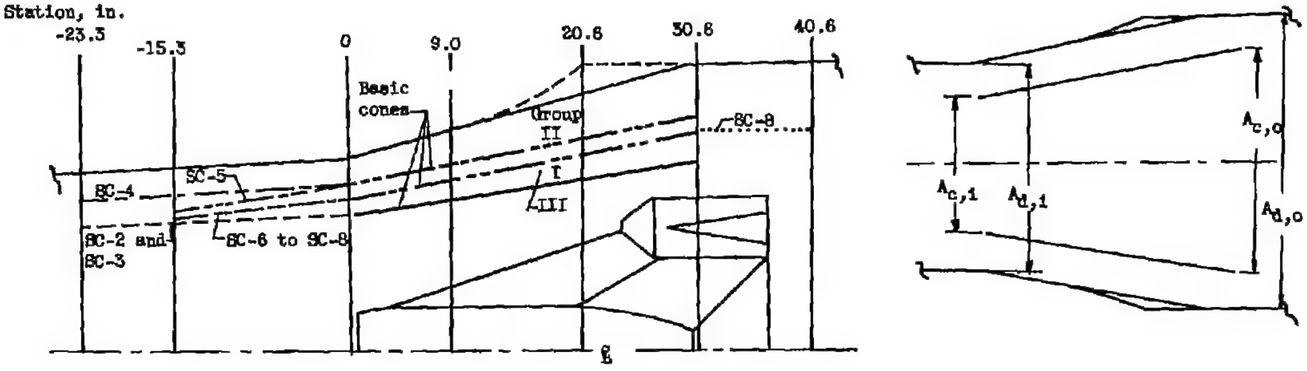


Figure 7. - Typical vortex-generator installation. (Upstream view.)



Configuration	Symbol	Group	Station						${}^aA_{c,i}/A_{d,i}$	${}^aA_{c,o}/A_{d,o}$	${}^aA_{c,o}/A_{c,i}$	$\frac{A_{d,o}-A_{c,o}}{A_{d,i}-A_{c,i}}$	Remarks
			-23.5	-15.3	0	9.0	30.6	40.6					
			Radius of splitter cone, in.										
SC-1	————	I	---	---	$11\frac{1}{2}$	$12\frac{1}{2}$	$15\frac{3}{4}$	---	0.52	0.38	1.50	2.65	VG-2 installed.
SC-2	— — —		$10\frac{1}{2}$	---	$11\frac{1}{2}$	---	$15\frac{3}{4}$	---	.49	.38	1.80	2.93	
SC-3	— — —		$10\frac{1}{2}$	---	$11\frac{1}{2}$	---	$15\frac{3}{4}$	---	.49	.38	1.80	2.93	[b]Vortex generators inside cone at station 0.
SC-4	——-—	II	$12\frac{1}{2}$	---	$13\frac{3}{4}$	---	$19\frac{5}{8}$	---	0.70	0.82	2.09	3.03	
SC-5	———--		---	$11\frac{1}{2}$	$13\frac{3}{4}$	---	$19\frac{5}{8}$	---	.58	.82	2.42	2.04	
SC-6	————-	III	---	11	$12\frac{1}{2}$	---	$18\frac{3}{8}$	---	0.52	0.55	2.38	2.14	
SC-7	————-		---	11	$12\frac{1}{2}$	---	$18\frac{3}{8}$	---	.52	.55	2.38	2.14	[b]24 Vortex generators at inside of cone at station 0.
SC-8	....		---	11	$12\frac{1}{2}$	---	$18\frac{3}{8}$	$18\frac{3}{8}$	.52	(c)	(c)	2.14	[b]24 Vortex generators at inside of cone at station 0.

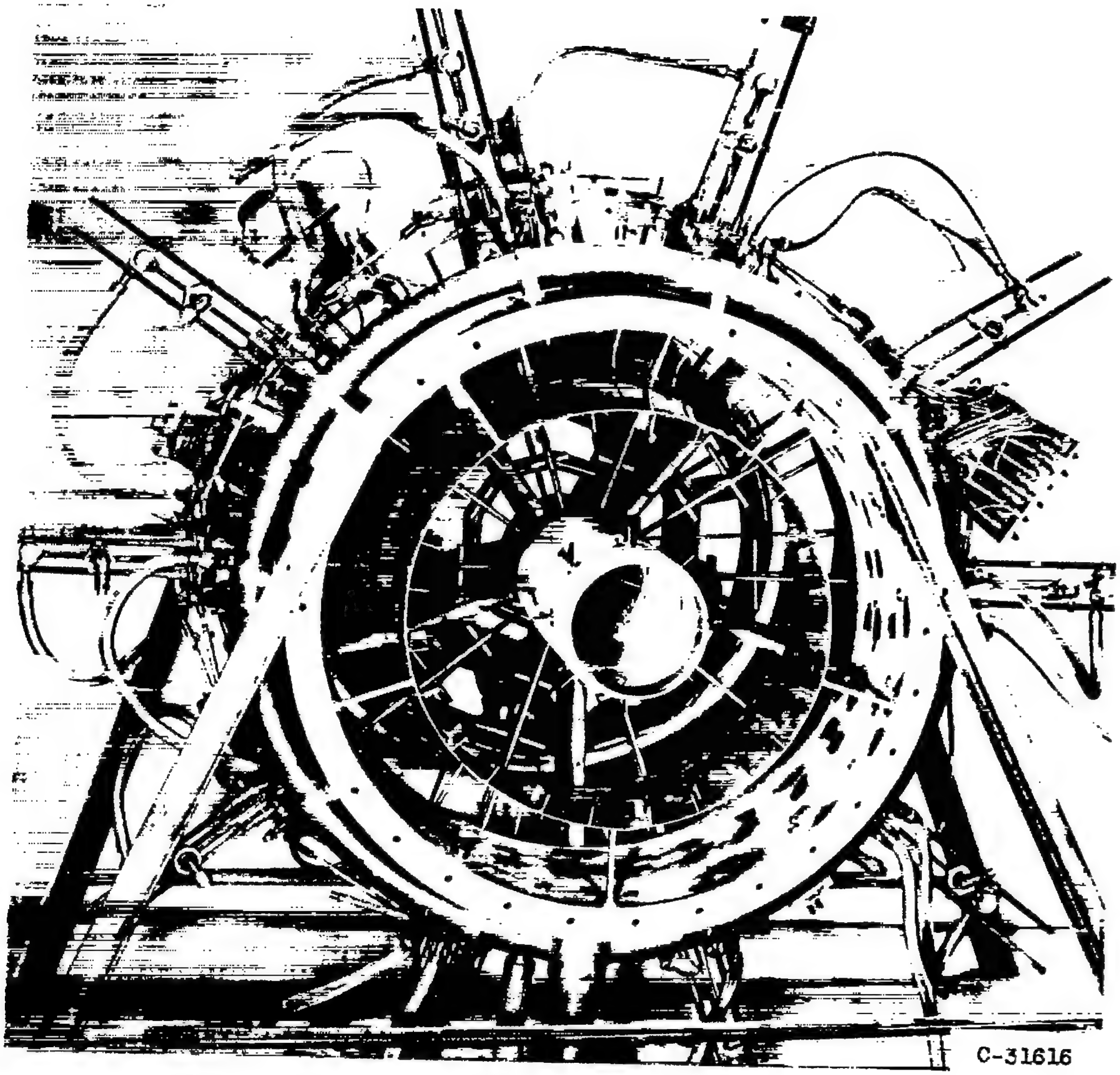
[a]Area of flame-holding elements accounted for.

[b]Vortex generators were identical with those used on the center-pilot extension (see fig. 4) and may be seen in figure 8(b).

[c]Effective area indeterminate because of flame-holder wakes.

(a) Description of configurations.

Figure 8. - Splitter-cone configurations.



(b) Typical installation (upstream view).

Figure 8. - Concluded. Splitter-cone configurations.

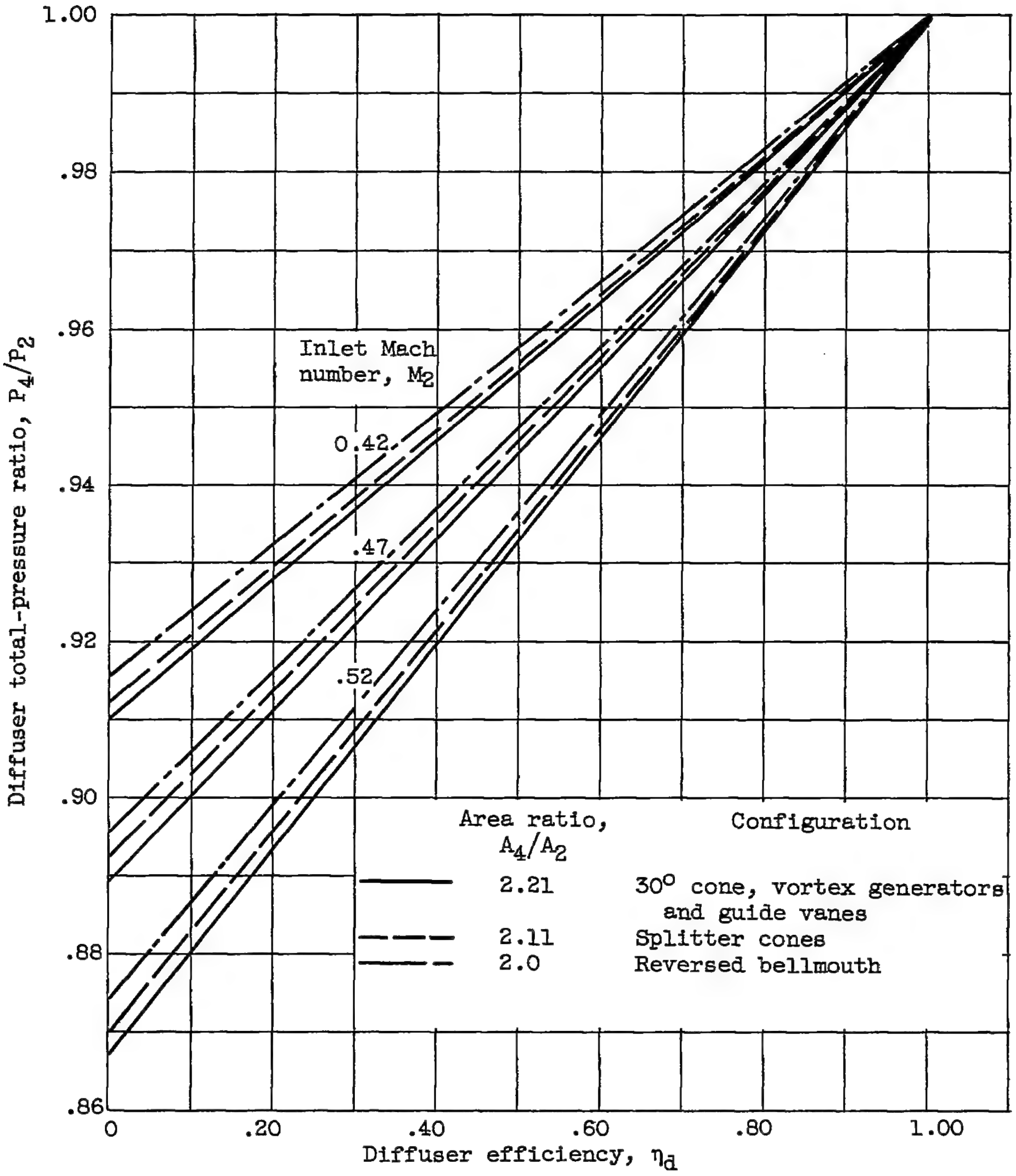


Figure 9. - Variation of diffuser total-pressure ratio with diffuser efficiency for various diffuser Mach numbers and area ratios.

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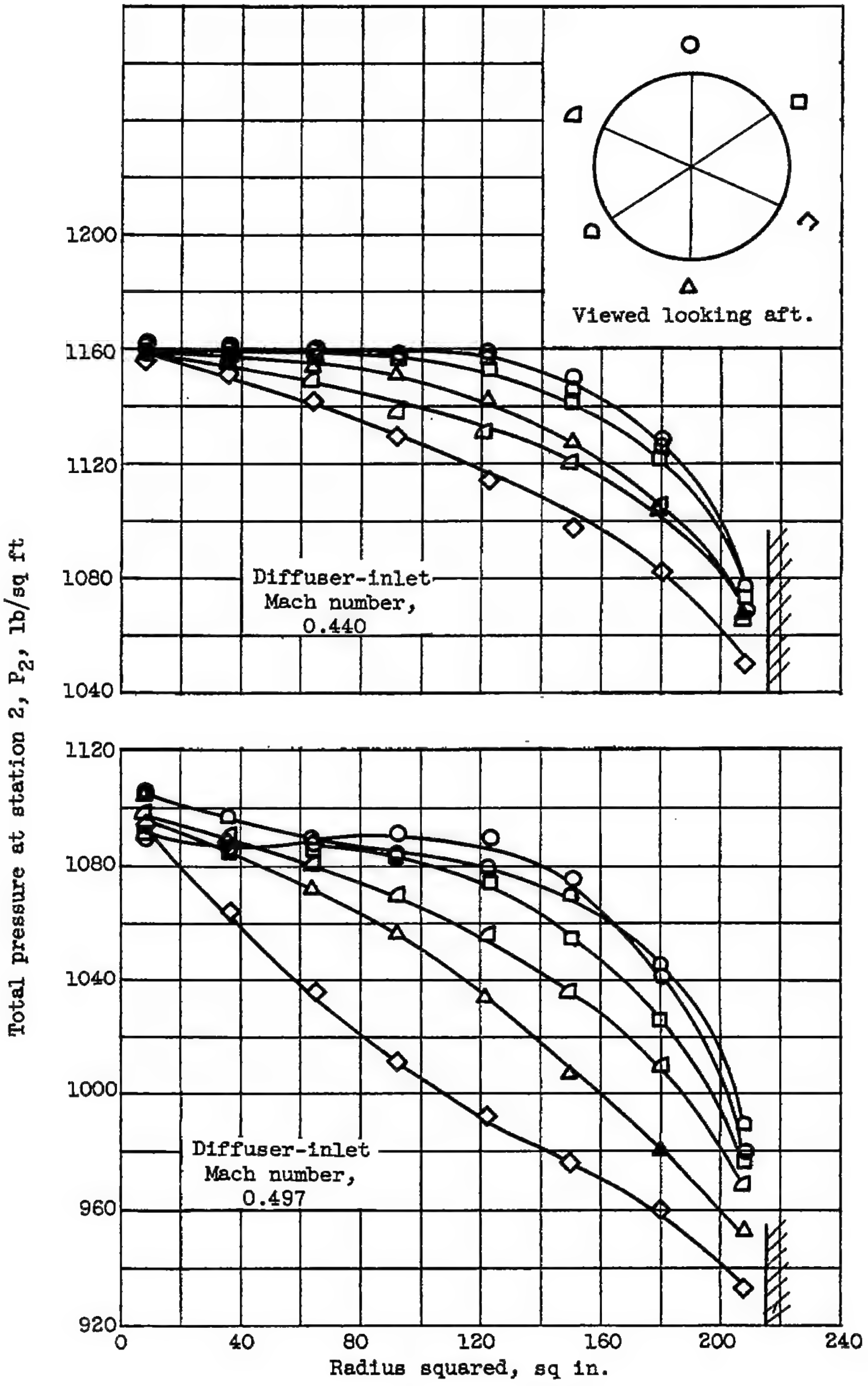
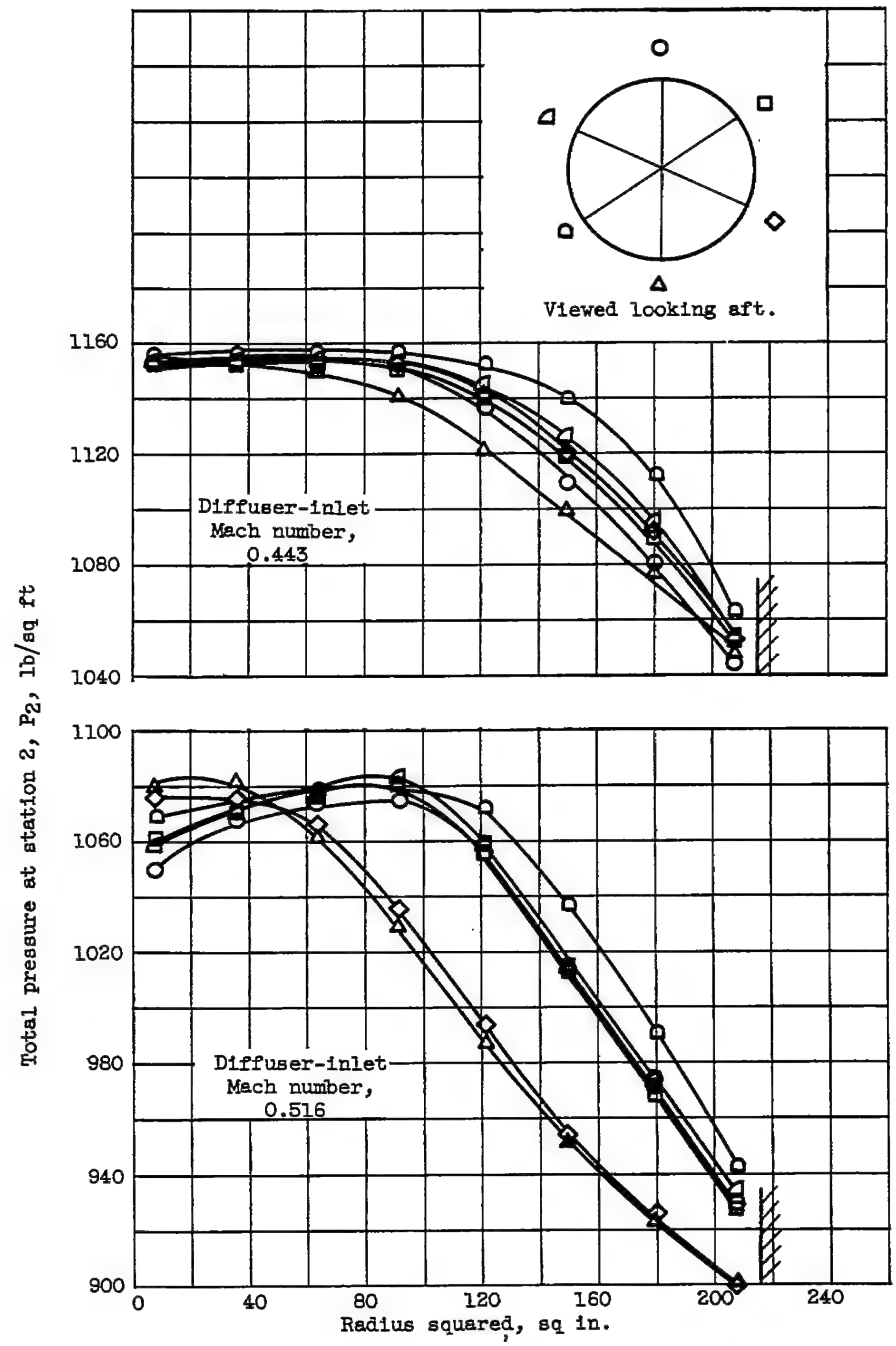


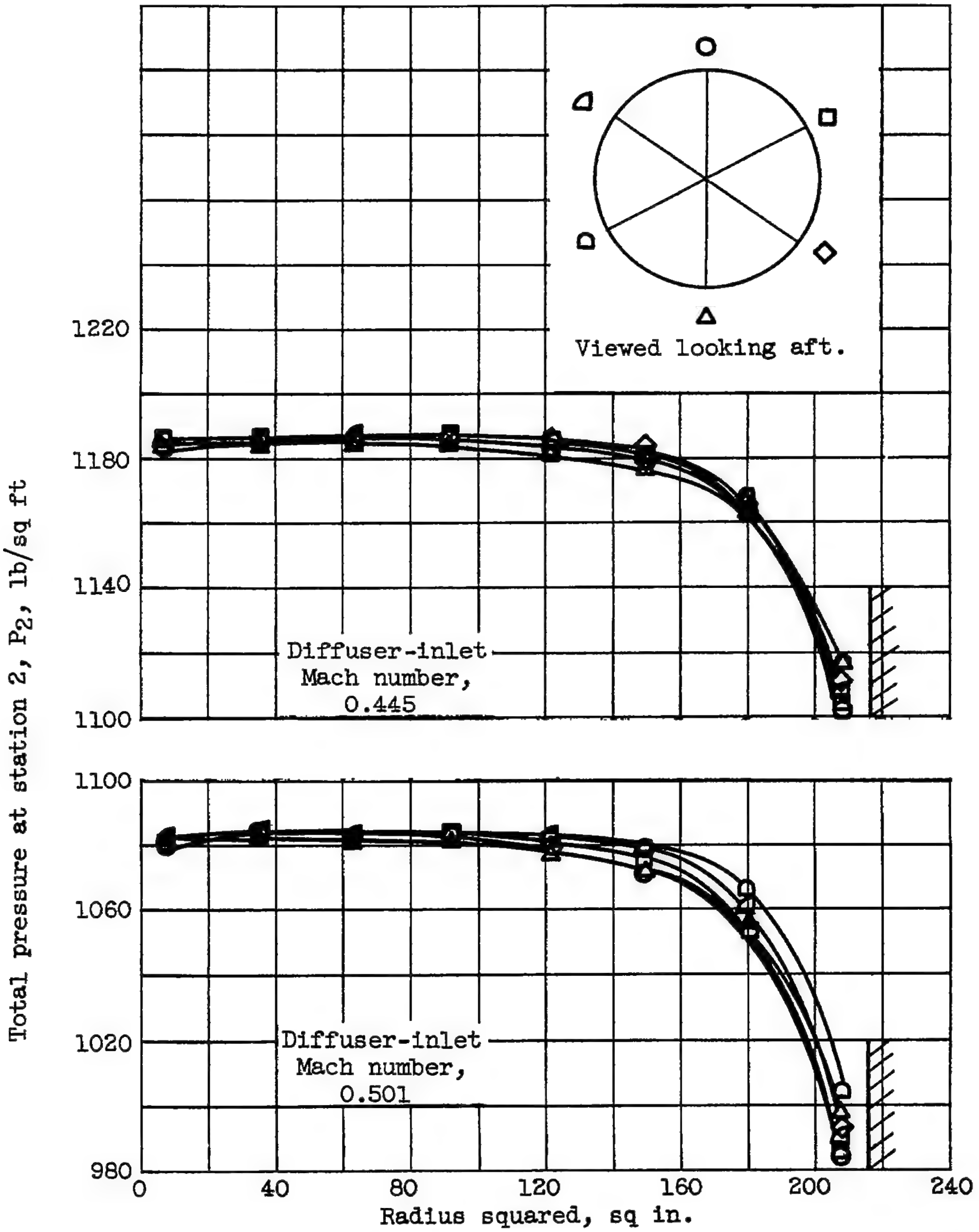
(a) Inlet condition A.

Figure 10. - Diffuser-inlet total-pressure profiles. (Station 2.)



(b) Inlet condition B.

Figure 10. - Continued. Diffuser-inlet total-pressure profiles. (Station 2.)



(c) Inlet condition C.

Figure 10. - Concluded. Diffuser-inlet total-pressure profiles. (Station 2.)

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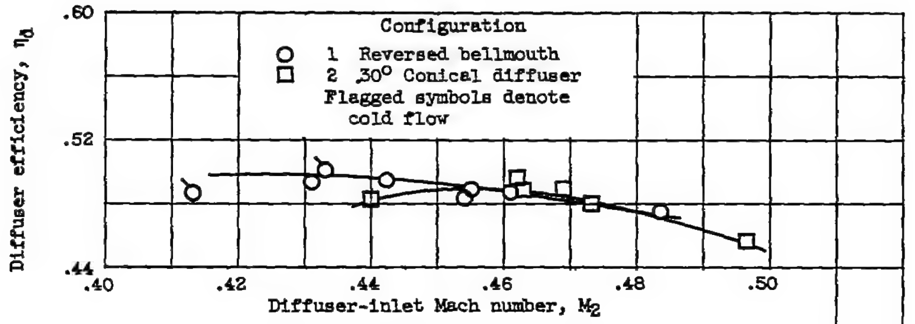
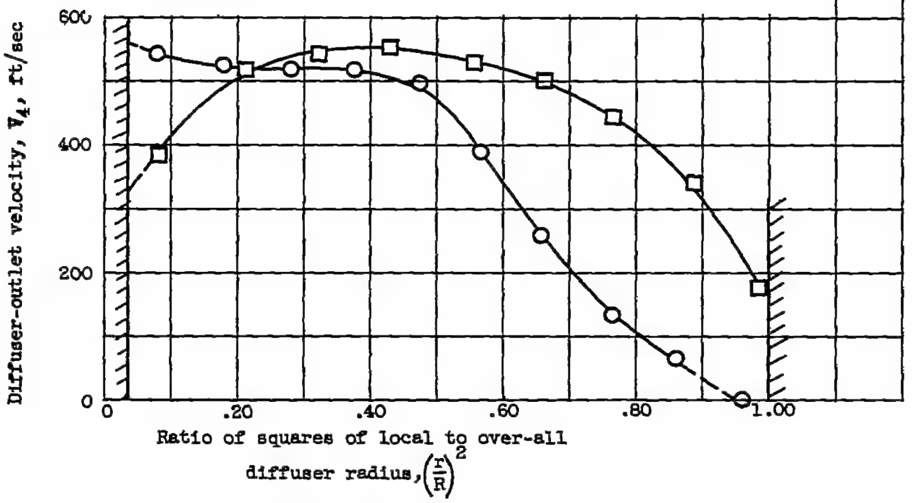
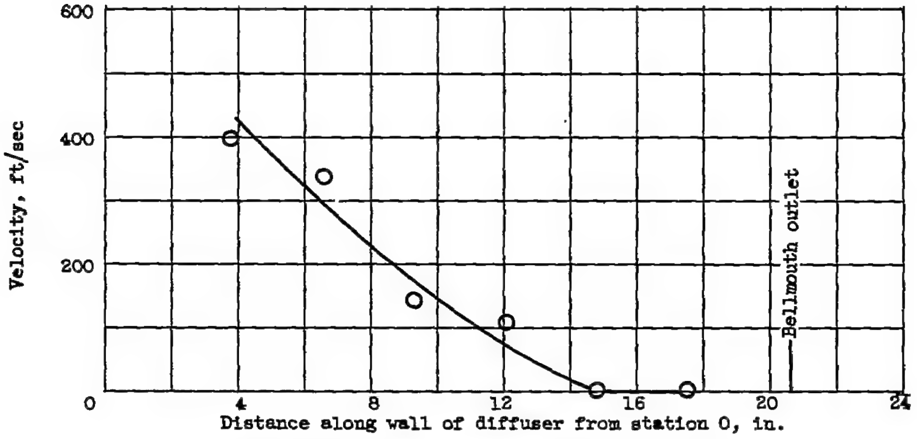
CV-5



(a) Variation of diffuser efficiency with diffuser-inlet Mach number.



(b) Radial velocity distribution at diffuser outlet. Diffuser-inlet Mach number, M_2, 0.46±0.01.



(c) Longitudinal velocity distribution along wall of diffuser. Diffuser-inlet Mach number, M_2, 0.46±0.01.

Figure 11. - Performance of reversed-bellmouth and 30° conical diffusers (configurations 1 and 2); inlet condition A.

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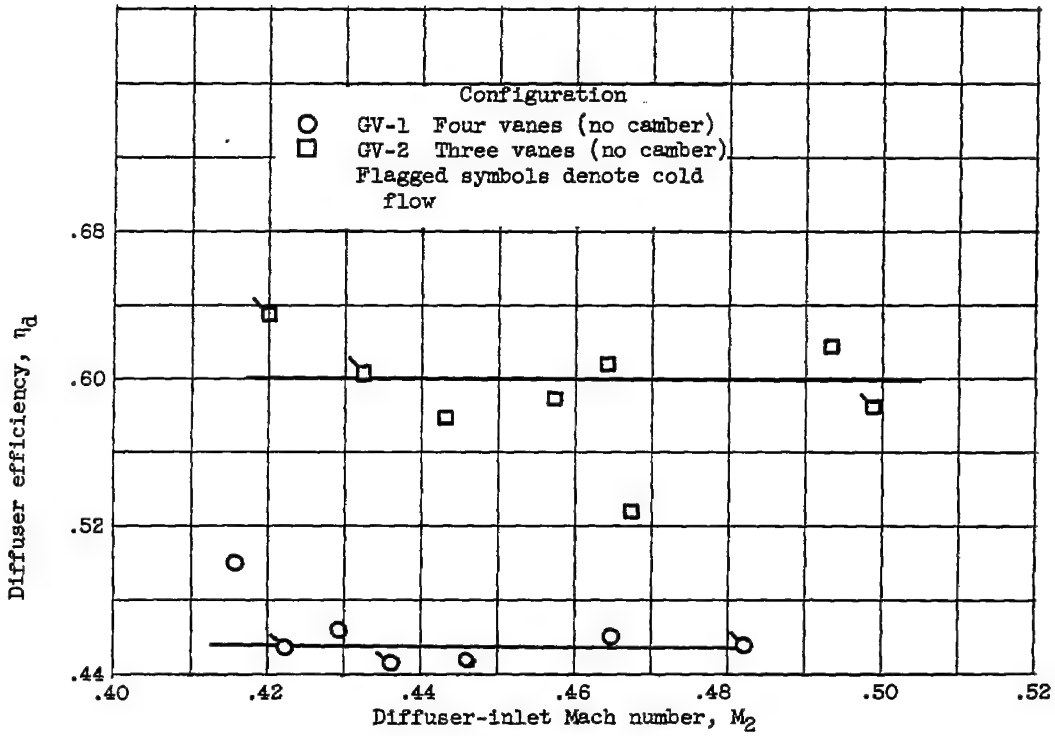
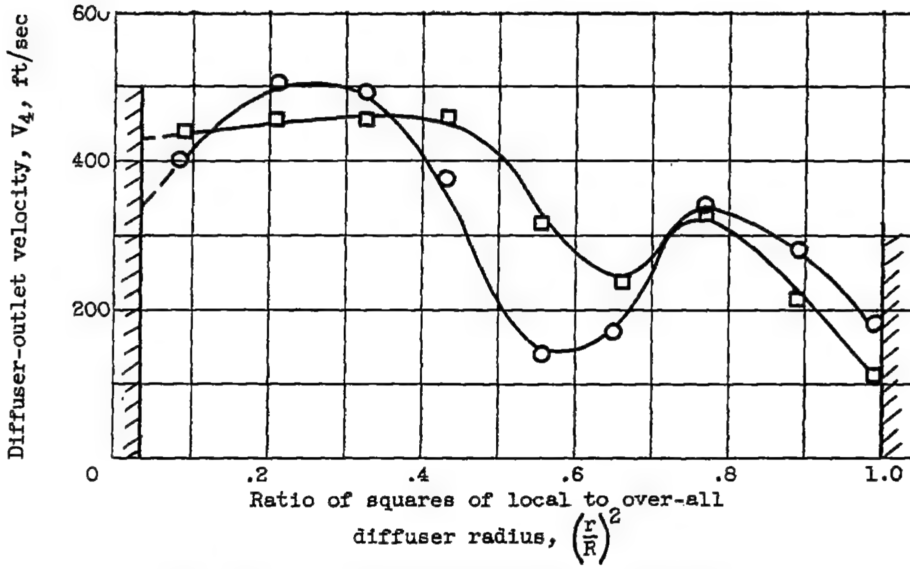


(a) Variation of diffuser efficiency with diffuser-inlet Mach number.



(b) Radial velocity distribution at diffuser outlet. Diffuser-inlet Mach number, M_2, 0.46±0.01.

Figure 12. - Performance of guide-vane configurations. Inlet condition B.

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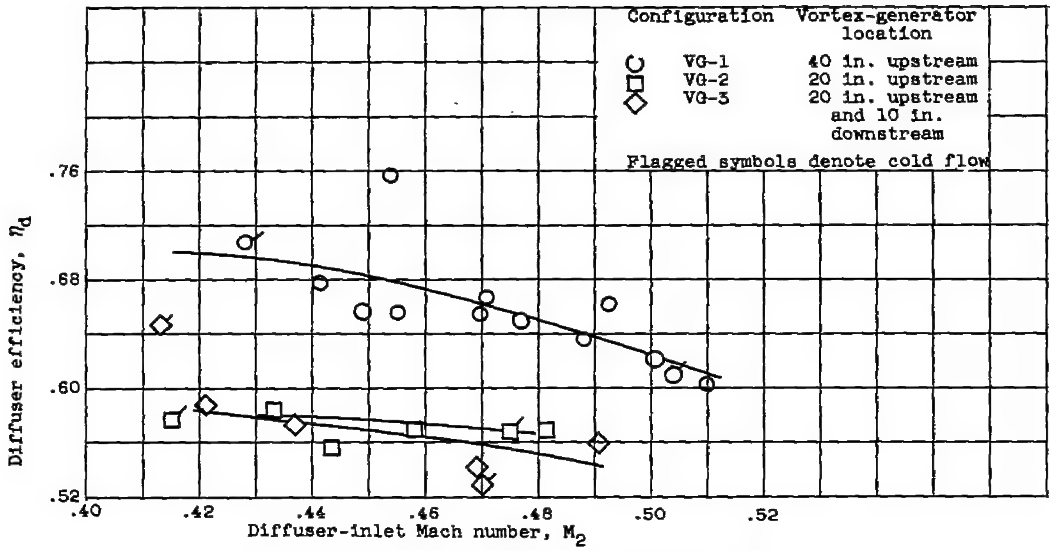
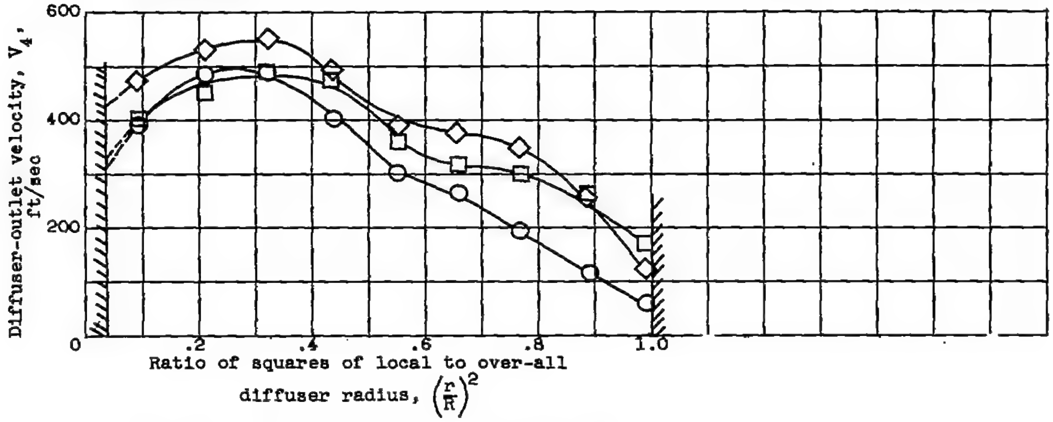
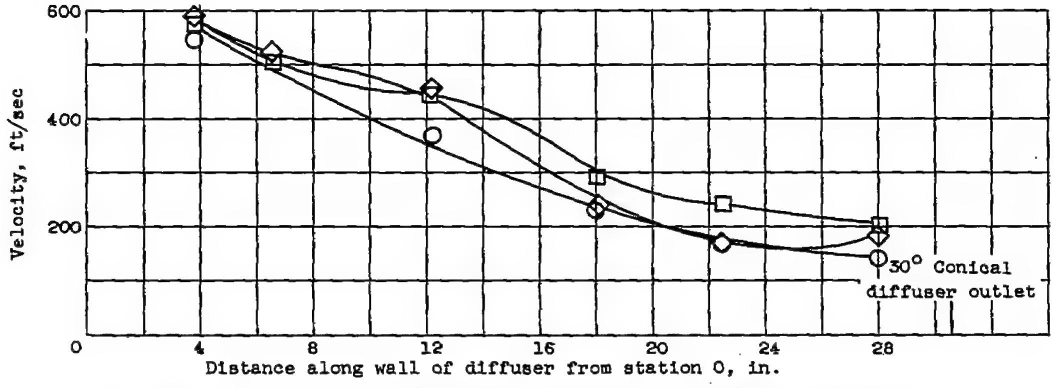
CV-5 back



(a) Variation of diffuser efficiency with diffuser-inlet Mach number.

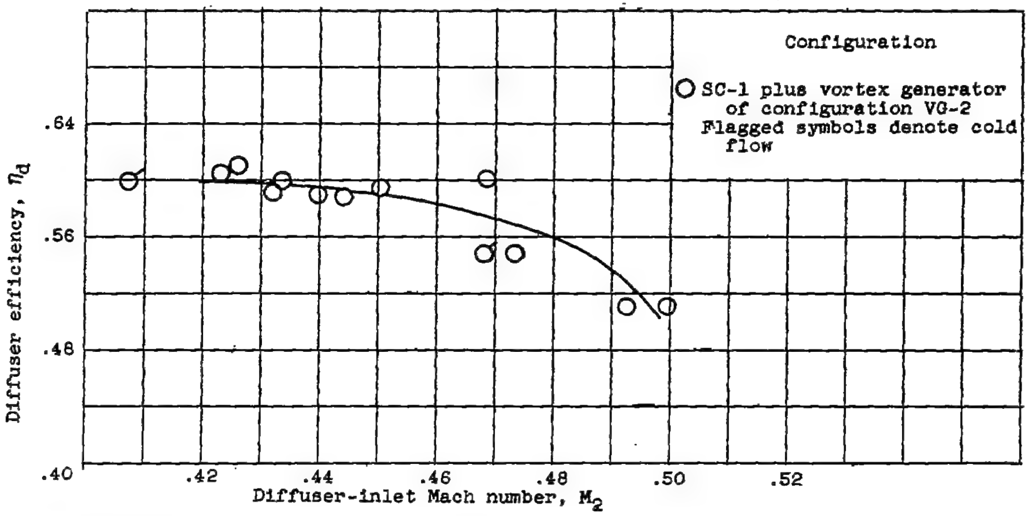


(b) Radial velocity distribution at diffuser outlet. Diffuser-inlet Mach number, M_2, 0.46±0.01.

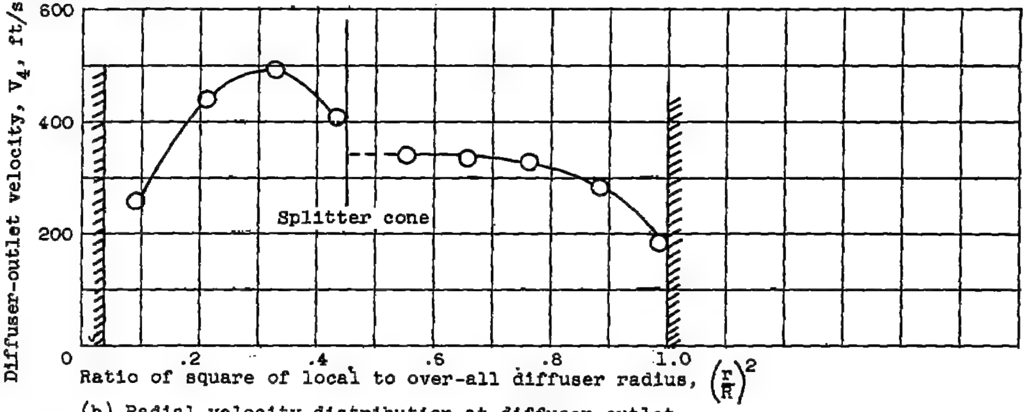


(c) Longitudinal velocity distribution along wall of diffuser. Diffuser-inlet Mach number, M_2, 0.46±0.01.

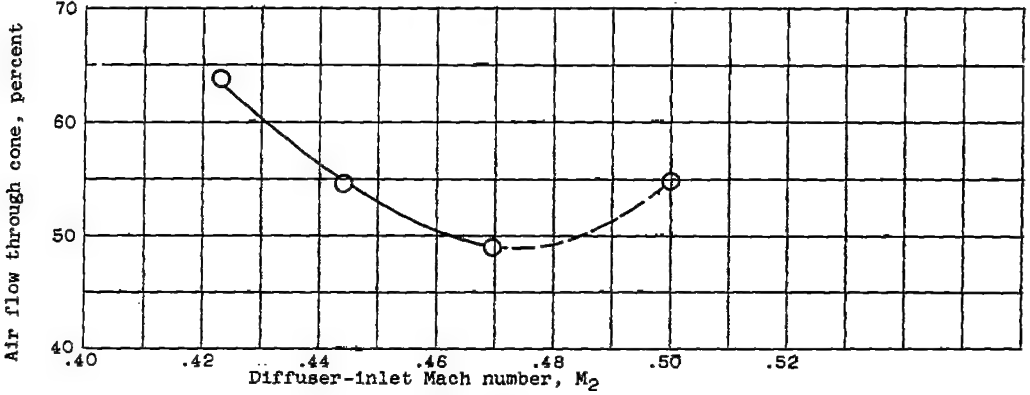
Figure 13. - Performance of vortex-generator configurations with inlet condition B.



(a) Variation of diffuser efficiency with diffuser-inlet Mach number.



(b) Radial velocity distribution at diffuser outlet. Diffuser-inlet Mach number, M_2, 0.46 ±0.01.



(c) Effect of diffuser-inlet Mach number on air flow through splitter cone.

Figure 14. - Performance of splitter-cone configurations of group I. Inlet condition B.

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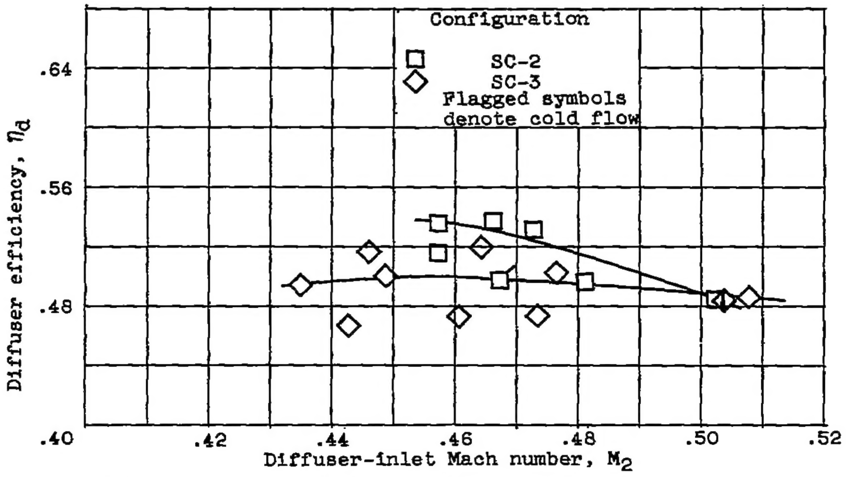
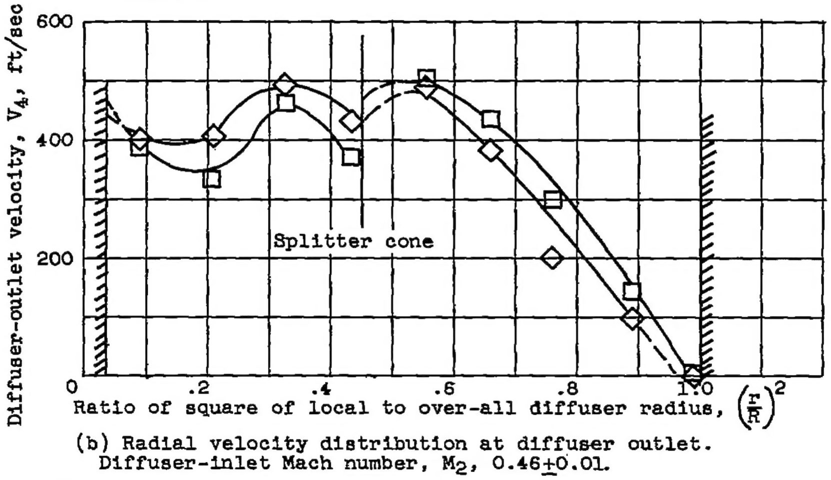
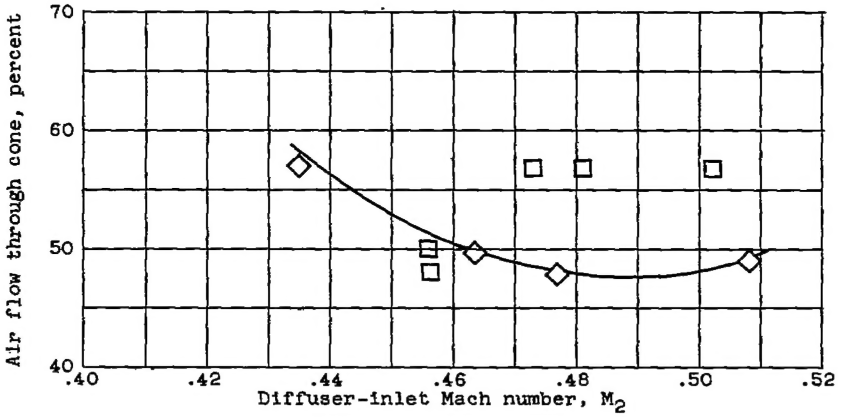


(a) Variation of diffuser efficiency with diffuser-inlet Mach number.

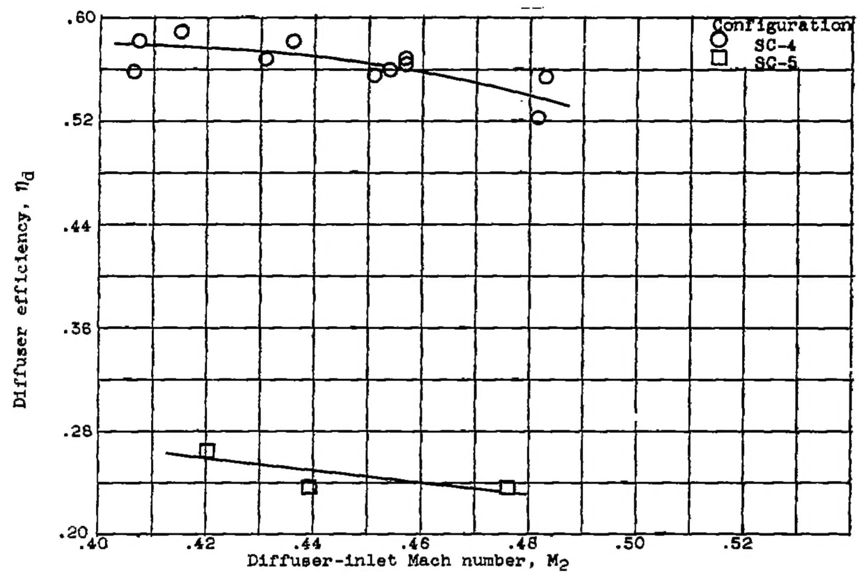


(b) Radial velocity distribution at diffuser outlet. Diffuser-inlet Mach number, M_2, 0.46±0.01.

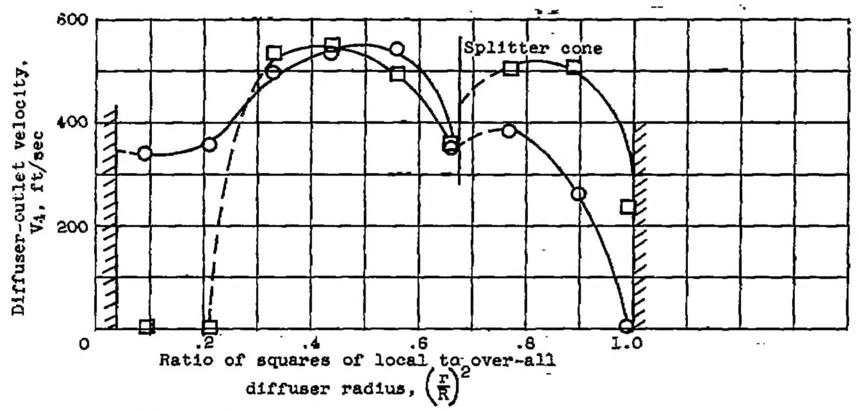


(c) Effect of diffuser-inlet Mach number on air flow through splitter cone.

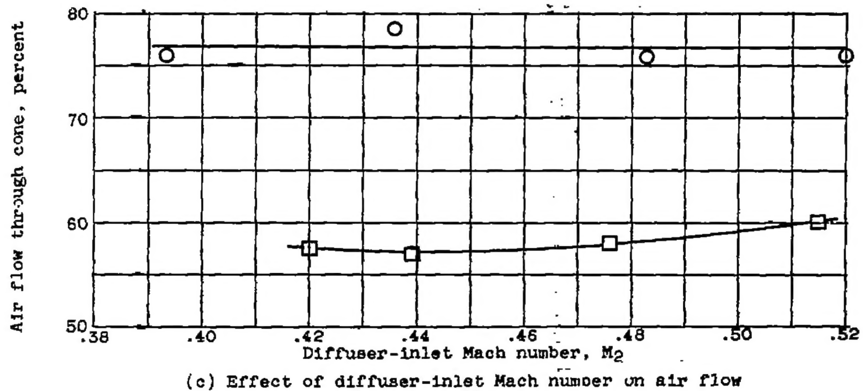
Figure 15. - Performance of splitter-cone configurations of group I. Inlet condition C.



(a) Variation of diffuser efficiency with diffuser-inlet Mach number.



(b) Radial velocity distribution at diffuser outlet. Diffuser-inlet Mach number, M_2, 0.46±0.01.



(c) Effect of diffuser-inlet Mach number on air flow through splitter cone.

Figure 16. - Performance of splitter-cone configurations of group II. Inlet condition C.

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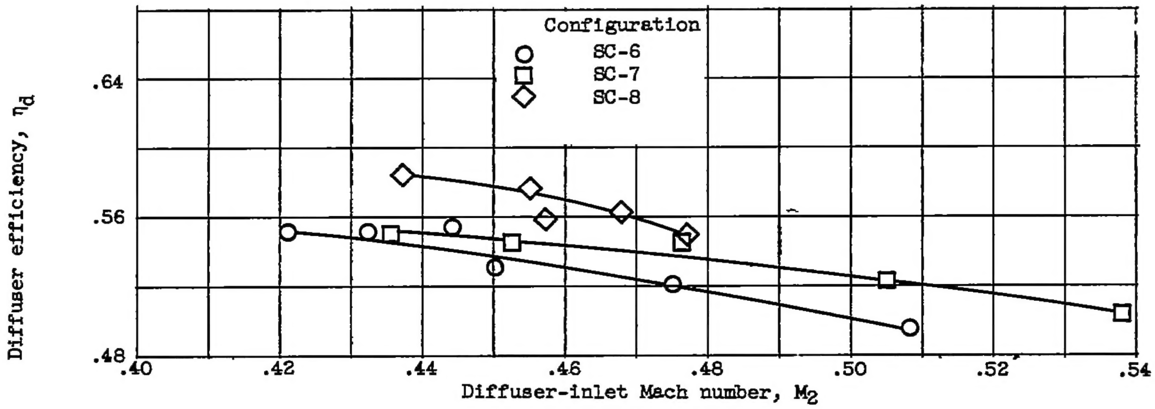
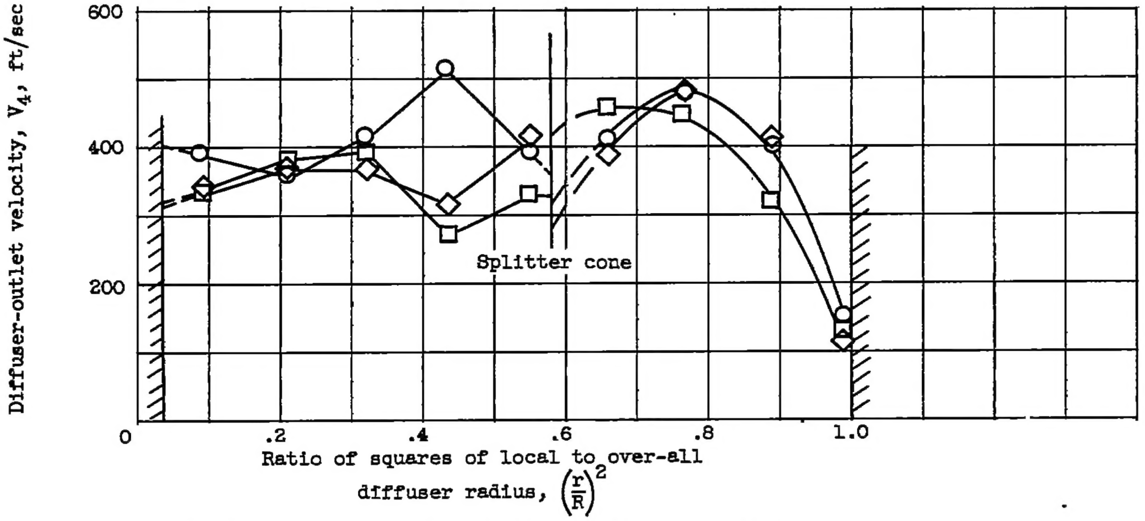
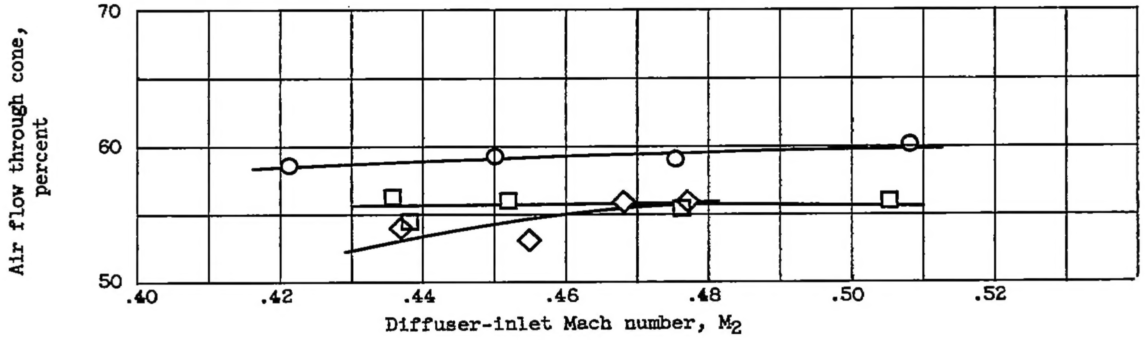


(a) Variation of diffuser efficiency with diffuser-inlet Mach number.



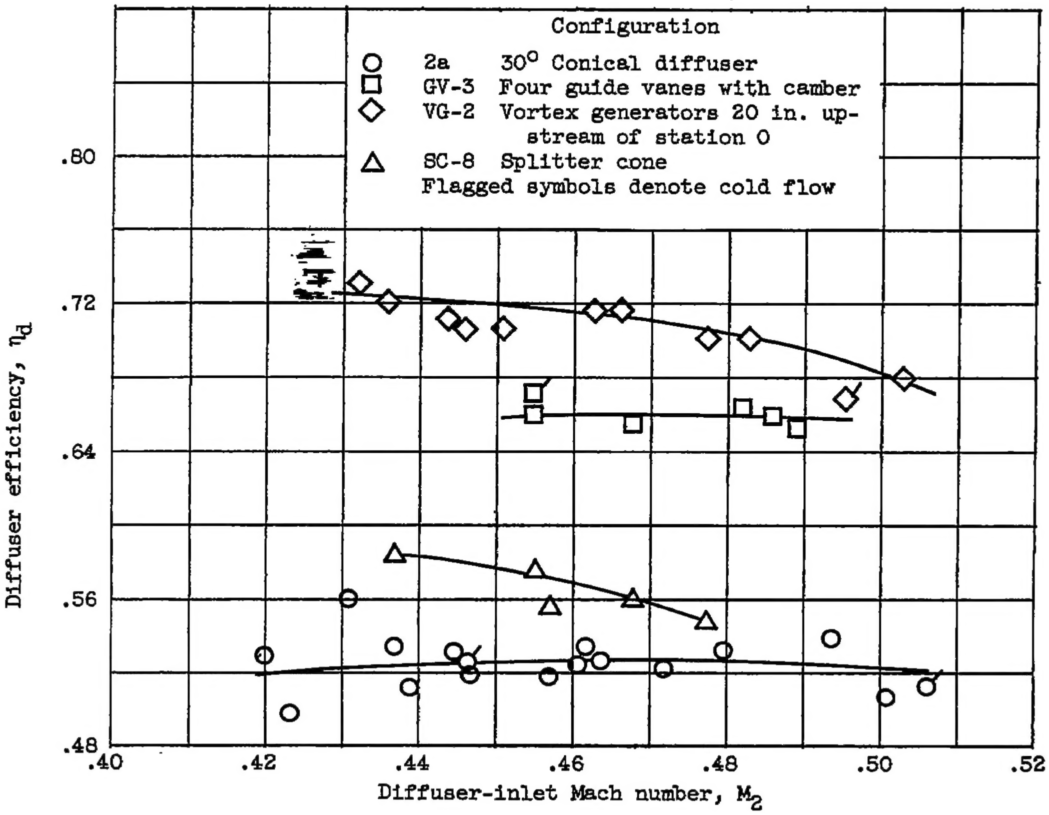
(b) Radial velocity distribution at diffuser outlet. Diffuser-inlet Mach number, M_2, 0.46 ±0.01.



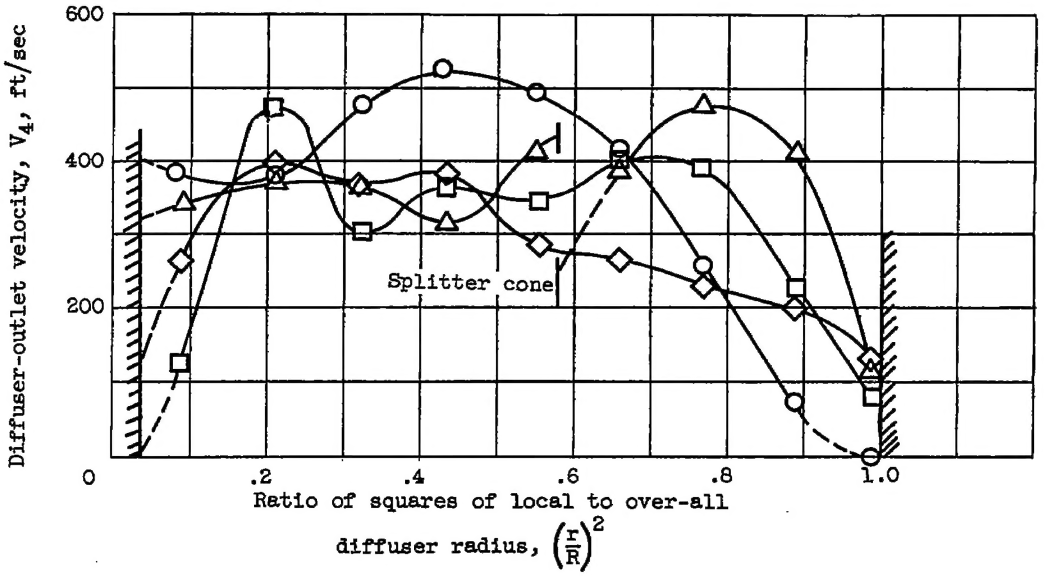
(c) Effect or diffuser-inlet Mach number on air flow through splitter cone.

Figure 17. - Performance of splitter-cone configurations of Group III. Inlet condition C.

3161



(a) Variation of diffuser efficiency with diffuser-inlet Mach number.



(b) Radial velocity distribution at diffuser outlet. Diffuser-inlet Mach number, M_2, 0.46±0.01.

Figure 18. - Comparison of various diffuser types. Inlet condition C.

[redacted]

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